ECONOMIC ANALYSIS OF
MARINE INDUSTRIAL FISHERIES

by

JULIO ALEJANDRO PEÑA TORRES

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Economics Department
Queen Mary & Westfield College
University of London

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ABSTRACT

This thesis is a collection of essays on the problem of overfishing in multi-firm fisheries with a common property fish stock. We focus on the case of marine industrial fisheries, where the costs of preventing free riding tend to preclude cooperative harvesting. We study the overfishing problem by analysing harvesting incentives that stem from variations in (i) technological (cost, production and biological growth) functions, (ii) institutional factors (access schemes, regulatory agencies' instruments and their monitoring and enforcement powers, harvesting competition), and (iii) objective functions (private firms' planning horizons, welfare functions).

Chapter 2 discusses conditions under which a fishing collapse can occur and examines the commonly held argument that fishing collapse is a public bad. Chapter 3 studies Chilean fishing regulations over the last five decades. The regulator's persistent inability to enforce annual quotas is analysed. Distributive disputes and triggered lobbying powers are examined. The late 1980s controversies over a new Chilean fishing law are analysed in-depth from this perspective. Chapter 4 explains the main motivations and key assumptions leading us to the oligopoly harvesting models of chapters 5 (static setting) and 6 (dynamic setting). These models focus on a deterministic single fish species and a single sector harvesting fishery composed of profit maximizing and price taking private firms that compete with each other by following non-cooperative harvesting strategies. These models examine the overfishing rankings that result from comparing Cournot-Nash and Stackelberg equilibria. First best and second best welfare benchmarks are considered. The Cournot-Nash setting is intended to illustrate a large number oligopolistic fishery, while the Stackelberg equilibrium is meant to be a first approximation to analyse the implications of harvesting fisheries subject to industrial concentration. Empirical evidence suggesting the presence of industrial concentration in a series of important marine industrial fisheries is described in chapters 3 and 4.

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To Beatriz

To my parents

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CHAPTER 1
INTRODUCTION.

(1.A) Basic issues.

This thesis is a collection of essays on the problem of overfishing in multi-firm fisheries with a common property fish stock. The objective is enlarging our understanding of the incentive structures, and underlying technological and institutional restrictions, that condition individual firms' harvesting decisions and their effects on the overfishing of common property fish populations. Although policy oriented prescriptions are not a central part to this thesis, some efforts are devoted to this aspect.

This thesis focuses on the case of marine industrial fisheries, where the costs of preventing free riding tend to preclude the possibility of self-enforced or credible cooperative harvesting strategies. Non-cooperative harvesting implies that firms' fishing strategies fail to fully internalize the externality brought about by common property. The analysis concentrates on the case of a deterministic single fish species and a single sector harvesting fishery composed of profit maximizing and price taking private firms that compete with each other by following non-cooperative harvesting strategies.

Commonality leads to several different allocative inefficiencies, each of which is associated with an inefficient dissipation of the Ricardian rents in the common property fish stock. Rent dissipation can arise from an excessive accumulation of productive capacity, possibly as a strategy to justify and acquire user rights upon the common pool resource (i.e., Munro, 1982; Eggertsson, 1990). Sometimes, inefficiencies can arise as the result of inefficient input use. For instance, in cases where only one productive input, within a multi-input technology allowing for substitution effects, faces binding regulatory controls aimed to control total harvesting (i.e., Gould, 1972; Munro and Scott, 1985). Rent dissipation may stem from rent seeking efforts, originating from distributive disputes among rival interest groups competing for fish stocks' rents (Wise, 1984; Miles, 1989). Rent dissipation may also arise from excessive harvesting competition among multiple non-cooperative harvesters (Clark, 1980; Levhari and Mirman, 1980). The latter is the rent dissipation process which is the main focus of this thesis. Rent seeking strategies related to fishing regulation, and underlying distributive disputes, are also discussed.

Excessive harvesting or overfishing can be analysed from different perspectives. The emphasis depends on the priority assigned to different aspects of this problem. On occasions the emphasis is on issues of long run sustainability. Marine biologists are prompt to emphasize this aspect (i.e., Idyll, 1973; Gulland, 1988). This profession has traditionally cautioned against the risk of extinction of the fish species under common property. Economists have been increasingly involved in this debate since the mid 1970s (i.e., Clark, 1973; Berck, 1979; Hartwick, 1982; Clemhout and Wan, 1986; Weitzman, 1992; Swanson, 1993). They have usually considered wider aspects of sustainability, for example, by analysing the problem of *economic* collapse (i.e., Lewis and Schmalensee, 1979, 1982). Specificity of capital stocks and irreversibility effects play a key role in the discussion of economic fishing collapse (Arrow and Fisher, 1974; Weitzman, 1992). Chapter 2 surveys and addresses the latter issues.

We study the problem of excessive harvesting competition by analysing the changes in harvesting incentives and their effects upon overfishing outcomes arising from variations in: (i) technological (cost, production and biological growth) functions, (ii) institutional factors (access schemes, regulatory agencies' instruments and their monitoring and enforcement powers, harvesting competition), and (iii) objective functions (private firms' planning horizons, welfare functions). More specific questions related to these issues are explained in what follows.

(1.B) Specific objectives.

This thesis examines two closely related groups of issues: regulation and market structure in common pool marine fisheries.

(a) Regulation.

First, we analyse some aspects of the regulation of common pool fisheries. We discuss how different emphasis on different aspects of the commonality issue imply different regulatory objectives. Chapter 2 discusses long run sustainability objectives. This chapter analyses technological and institutional factors affecting the occurrence of fishing collapse. Technological factors (cost, harvesting, and biological growth functions) are discussed in some detail. It is argued that under some conditions a fishing collapse could be welfare optimal.

In chapter 3 we study the case of Chilean fishing regulations, particularly those related to access restrictions and catch quotas. We analyse fishing regulators' persistent inability to enforce annual catch quotas. Different restrictions faced by regulatory agencies, and the impact on regulatory outcomes, are studied. We discuss the possibility of regulatory capture by private interest groups and analyse distributional conflicts and related lobbying strategies. We also analyse policy priorities and their changes over the last five decades and give a detailed analysis of the enactment of the Chilean 1991 Fishing Law.

In chapters 5 and 6 we develop models to illustrate how changes in the regulator's powers can change the assessment of overfishing inefficiencies. We do this in the context of oligopolistic harvesting games in static and dynamic settings. We make explicit comparisons between first best and second best welfare solutions. The latter are defined by welfare optimization problems where a social planner has control only upon one firm among $n \geq 1$ remaining rival harvesting firms. This exercise is a simplified illustration of a fishing regulator who has limited control and enforcement powers upon the regulated firms' actions. By contrast, the first best welfare yardstick assumes that the social planner has full control upon all harvesting firms that exploit the common pool fish stock. The use of second best welfare solutions allows us to illustrate arguments of *constrained* optimality. The use of constrained optimality benchmarks tends to reduce the parameter ranges in which oligopolistic private firms harvest inefficiently. The explicit modelling of these ideas within multi-firm harvesting games is one of the contributions of this thesis.

(b) Market structure

The second set of questions concerns overfishing incentives within the context of multi-firm harvesting competition games. This thesis offers a contribution to the literature on fishery economics by considering common pool marine fisheries subject to industrial concentration in harvesting sectors; that is, fisheries with a few relatively large harvesting firms competing with numerous smaller rival harvesters. Chapters 3 and 4 provide empirical evidence that supports the relevance of studying harvesting incentives in this type of fishery setting. The case of Chilean marine pelagic fisheries is examined in detail. Other examples considered are the Peruvian anchovy fishery of the second half of the 1960s and early 1970s, and the US tuna fishery during the 1970s.

The study of marine fisheries subject to industrial concentration has traditionally focused on processing firms with monopsonistic or oligopsonistic powers with respect to harvesting firms (Crutchfield and Pontecorvo, 1969; Clark and Munro, 1980; Munro, 1982; Schworm, 1983; Stollery, 1987). Chapter 4 provides a brief summary of these ideas. In this thesis we pursue a different approach. By excluding processing firms with mono(oligo)psonistic powers from the analysis, we can pursue a more detailed analysis of harvesting competition strategies at fisheries with concentration amongst harvesting firms.

This allows us to explore in greater detail the changes in harvesting incentives and in overfishing outcomes that arise from different assumptions about: (i) the type of strategic interactions among harvesting firms, distinguishing between different sources of strategic interaction and between different types of conjectures about rivals' strategic reactions; (ii) the optimization rules pursued by different types of harvesting firms (small/large size), contrasting static with dynamic optimization rules; and (iii) technological (cost, production, and biological growth) functions.

Chapters 5 and 6 develop models of multi-firm harvesting competition games in static and dynamic optimizing settings. They model industrial concentration by assuming the existence of a harvesting firm that is a Stackelberg leader which may have a productivity advantage over the numerous followers. The leader-followers setting is one of the simplest ways to represent more active features of strategic interaction, relative to the passive strategic conjectures of Cournot-Nash settings. We use the concept of hierarchical Stackelberg equilibrium as a first approximation to analyse the implications of common pool harvesting fisheries subject to industrial concentration.

By contrast Cournot-Nash equilibria are the modelling settings in which the tragedy of the commons has been more frequently analysed since the early 1980s (Clark, 1980; Levhari and Mirman, 1980; Cornes and Sandler, 1983; Cornes, Mason and Sandler, 1986; Plourde and Yeung, 1989). Conjectural variations equilibria have also been used in common pool fishery models (i.e., Cornes and Sandler, 1983; Mason, Sandler and Cornes, 1988).

The studies cited above attempted to generalize results with respect to the predominant view, during the 1950s-1970s, of the overfishing problem. In this period strategic considerations were neither discussed nor mentioned as factors affecting harvesting actions (i.e., Gordon, 1954; Scott, 1955; Smith, 1968 and 1970; Quirk and Smith, 1970; Brown, 1974). Open access was a predominant assumption in these earlier studies. Most of them also *assumed* that firms competing for the common pool resource's rents would necessarily behave as static profit optimizing agents. No attempt to endogeneize the latter feature was considered.

In this thesis we aim to contribute to the existing literature on multi-firm harvesting competition in a number of ways. First, we aim to complement the existing studies on oligopolistic harvesting games by offering consistent comparisons between Cournot-Nash and Stackelberg harvesting equilibria and the resulting overfishing outcomes. Chapter 5 does this within a static setting. Chapter 6 considers the existence of harvesting agents (private firms as well as the case of a social planner) which use dynamic optimizing decision rules. Very few papers have previously considered the modelling of hierarchical Stackelberg equilibria within the context of multi-firm harvesting competition games. For example, Levhari and Mirman (1980) and Dockner et al. (1989) consider a dynamic *duopoly* fishery which is analysed under Cournot-Nash and Stackelberg equilibria.

In chapters 5 and 6 we contribute to the latter type of analysis by considering closed entry *oligopoly* harvesting models, in static and dynamic settings, which allow us to examine how increasing numbers of rival firms affect the harvesting incentives, and the resulting overfishing, of firms competing under Cournot-Nash and Stackelberg equilibria. In each case we assess the overfishing outcome in terms of first best and second best welfare benchmarks. In each case we also consider the possibility of a leading firm with productivity advantages over her rivals and we examine the effects upon overfishing.

Cournot-Nash settings can be understood as a reasonable modelling approximation for harvesting fisheries where each firm tends to perceive its own production as negligible relative to the industry's total production. In these cases, the Nash assumption of rivals' passive strategic reaction to marginal changes in individual firms' actions seems to be reasonable. By contrast our leader-followers setting is intended to illustrate harvesting fisheries subject to industrial concentration.

A second contribution is the development of harvesting models in which we explicitly define and analyse, via survey oriented discussion and new models, how different types of externality affect the firms' harvesting incentives that underlie overfishing outcomes. Multi-firm harvesting models usually do not refer clearly to these different options for modelling externality effects within common pool fisheries.

Oligopoly models traditionally consider strategic interactions that stem from pecuniary effects. For example, oligopolistic firms with price setting powers in the product or input markets. Some oligopolistic harvesting models share this feature (i.e., Kamien, Levhari and Mirman, 1985; Cornes, Mason and Sandler, 1986; Mason, Sandler and Cornes, 1988; Dockner et al., 1989). In this thesis we exclude this source of strategic interactions. We partly do so based on an empirical motivation. Chapters 3 and 4 describe the latter. However, another important motivation has consisted in analysing and isolating the effects upon harvesting incentives of *technological* externalities directly associated with the common property of fish stocks.

The oligopoly harvesting models in chapter 5 and 6 help us to explore this issue. Chapter 5 considers a static *congestion* externality effect built into each firm's harvesting function. This modelling strategy differs from the standard treatment of congestion effects as an aggregate effect within the industry's production function. Our modelling allows us to analyse how different congestion levels affect the resulting overfishing under different oligopoly harvesting equilibrium concepts. Congestion effects introduce rival consumption among harvesting firms. This allows us to study the parameter ranges in which harvesting preemption corresponds to individual firms' optimal strategy. Harvesting preemption implies that a given firm increases her fishing effort in order to discourage rival firms' harvesting, via the effect of increasing the congestion problem. The cost of pursuing harvesting preemption is that it reduces each firm's harvesting productivity, the preemptive firm's productivity included.

Chapter 6 analyses oligopolistic firms' harvesting incentives that stem from a stock or *dynamic* externality effect. This corresponds to the impact that rival firms' current harvesting has on the future fish stock. This effect introduces intertemporal rival consumption among independent harvesting firms. Assuming the existence of private firms which dynamically optimize their individual intertemporal profits, we compare Cournot-Nash and Stackelberg harvesting stationary equilibria against welfare benchmarks (considering first best and second best solutions) that dynamically optimize the industry's *aggregate* intertemporal profits.

Our third contribution to the existing literature on oligopolistic harvesting games is related to the analyses performed within the dynamic optimizing setting of chapter 6. First, we model overfishing outcomes as the result of *endogenous* differences between the social scarcity value of the common pool fish stock and the marginal value assigned to it by non-cooperative, though dynamic profit optimizing, oligopolistic harvesting firms. This has not always been clearly brought out in previous dynamic oligopoly harvesting models (i.e., Clark, 1980; Levhari and Mirman, 1980; Dockner et al., 1989). Our approach allows an explicit discussion of the meaning of myopic decision rules and we are able to make a distinction between the concepts of static profit optimization and inefficient harvesting myopia.

Second, using the assumption of *closed entry* to the common pool fishery, we examine how exogenous increases in the number of rival firms affect the degree of inefficient harvesting myopia that is traditionally *assumed* for the case of non-cooperative individual harvesting firms. We develop this analysis for dynamic profit optimizing Cournot-Nash firms, and also for the case of a dynamic profit optimizing Stackelberg leading firm which competes in harvesting with numerous smaller followers, each of the latter behaving as a static profit optimizing agent. This type of analysis is absent from previous dynamic harvesting models that have considered Cournot-Nash as well as Stackelberg *duopoly* equilibria (i.e., Clark, 1980; Levhari and Mirman, 1980; Dockner et al., 1989; Plourde and Yeung, 1989).

(1.C) Modelling assumptions.

The models developed in chapters 5 and 6 are not aimed at explaining any specific fishing industry, even though some of their assumptions are prompted by the Chilean experience. The main objective of these modelling efforts is a better understanding of non-cooperative individual firms' harvesting incentives under different types of strategic interactions, due to different externality effects or to different types of conjectures about rivals' reaction, or to static versus dynamic intertemporal optimization rules.

For instance, we consider closed-entry harvesting models partly because restricted entry has been a predominant feature at national marine industrial fisheries, particularly since the late 1970s (Scott, 1988; Wilen, 1988). Our case study of Chilean pelagic fisheries shows that from the mid 1980s a *de facto* closed entry regulation has prevailed at the most heavily exploited marine industrial fisheries. Besides its empirical relevance, the closed entry assumption also helps us to study how exogenous increases in the number of firms with access to the common pool resource modify the harvesting incentives faced by different types (leader/follower; static/dynamic profit optimizer) of non-cooperative oligopolistic harvesting firms. This is an interesting question because it is related to the traditional intuition (Gordon, 1954; Scott, 1955) that numerous and relatively small harvesting firms will tend to behave as inefficient static profit optimizing agents when they compete in a non-cooperative fashion for the common pool fish stock's Ricardian rents.

The models in chapters 5 and 6 also consider harvesting firms subject to price taking behaviour, in input and output markets. This assumption is again partly justified by empirical motivation stemming from the case study of the Chilean (fish meal) pelagic fishing industry in Chapter 3. Moreover, there is also a theoretical justification for this assumption. Firms' price taking behaviour excludes the possibility of pecuniary externalities arising from the common property of fish stocks. This helps us to separately analyse the differences in individual firms' harvesting incentives that stem from different types of technological externalities, either in static or dynamic optimization settings. This analysis is a contribution to the prevailing economic literature on common pool fisheries subject to multi-firm harvesting competition[1].

(1.D) Thesis structure.

The organization of the thesis is as follows. Chapters 2 discusses long run sustainability issues related to objectives of fishing regulation. This chapter surveys and analyses the problem of fishing collapse. Fishing collapse is interpreted as either implying species biological extinction or the economic closure of fishing industries. Two main questions are explored in this chapter. First, which type of technological conditions (biological growth, cost, and harvesting functions) contribute to the occurrence of fishing collapses? Second, under what combination of welfare function and technological conditions can a fishing collapse be the welfare optimal solution?

Chapter 3 analyses the history of Chilean fishing regulations over the last five decades. The evolution of access restrictions and catch quota objectives is emphasized. Chile's most important marine industrial fisheries are examined, using newly collected data and analysis on the industrial structure of these fisheries. The main objective of this chapter is to understand important institutional factors that condition the results from fishing regulation. The historical and institutional analysis considers: policy priorities; the institutional organization of different regulatory

[1] A series of other assumptions, used in the static and dynamic multi-firm harvesting models in chapters 5 and 6, are essentially motivated by simplicity and tractability objectives. Among these assumptions we highlight: the use of a *strictly concave* biological growth function for the *single* common pool fish stock of chapter 6; the analysis of *steady state* solutions for the differential harvesting games in the same chapter; the focus on *deterministic* and *single sector* common pool fisheries; the assumption of a harvesting technology with a *single* variable fishing input; the analysis, in chapter 6, of a differential hierarchical Stackelberg harvesting game with a *single* dynamic profit optimizing firm (the leader) which competes with numerous *static profit optimizing* smaller follower firms. More specific descriptions of these and other minor assumptions are offered in the corresponding chapters.

agencies' tasks; the fishing regulator's informational restrictions; the main private interest groups affected by regulatory decisions and these interest groups' lobbying efforts to capture regulatory outcomes. A detailed account of the legislative process, to the Chilean (1991) fishing law and the distributional conflicts underlying it, is also provided.

Chapter 4 explains the main motivations leading us to develop the oligopoly harvesting models of chapters 5 and 6. Common basic assumptions are described and justified in this chapter. Empirical evidence suggesting the presence of industrial concentration at some important marine industrial fisheries is described. This information complements the previous description (chapter 3) of industrial concentration at the most important Chilean marine industrial (pelagic) fisheries. The evidence mentioned above motivates the type of oligopoly harvesting models developed in chapters 5 and 6. These models consider hierarchical Stackelberg equilibria as a first approximation to explore the implications of common pool fisheries subject to industrial concentration.

Chapter 5 develops and analyses a static oligopolistic harvesting competition model that incorporates the commonality problem by building a congestion externality effect in each firm's harvesting function. Cournot-Nash and Stackelberg equilibria are compared, contrasting the resulting overfishing in each case. First best and second best welfare benchmarks are used to analyse the overfishing result. The robustness of the overfishing ranking between Cournot-Nash and Stackelberg solutions is analysed with respect to changes in: (i) the relative magnitude of the congestion problem (versus a traditional effect of decreasing marginal productivity for the variable fishing input), (ii) the exogenous number of rival harvesting firms, and (iii) the productivity differences between the leading firm and the remaining smaller rival firms.

Chapter 6 also analyses the resulting overfishing ranking between Cournot-Nash and Stackelberg harvesting equilibria. In this case, however, overfishing is studied within a dynamic optimization setting. The commonality problem is incorporated via a *stock* or *dynamic* externality effect. First best and also second best welfare benchmarks are defined and used to assess the inefficiencies related to overfishing. The latter is endogenously deduced as the result of inefficient harvesting myopia; that is, the positive difference between the shadow scarcity value of the common pool resource and the marginal valuation assigned to it by non-cooperative independent harvesting firms. The dynamic model in chapter 6 allows us to study the impact of an increasing number of rival firms upon the degree of inefficient harvesting myopia. This exercise is developed for Cournot-Nash and Stackelberg solutions.

CHAPTER 2
ON LONG-RUN SUSTAINABILITY AND COLLAPSE.

(2.A) Introduction.

Two major sets of problems have attended the academic discussions and policy implementation of fishing regulations. On the one hand, the issue of inefficient rent dissipation arising from the common property of fish stocks. On the other hand, sustainability concerns about the long-run survival of the dynamic system (fish population) subject to economic depletion. This chapter focuses on the latter: it discusses the issue of *fishing collapse*, which is interpreted as either implying species biological extinction or the economic closure of fishing industries.

Two basic questions are addressed. First, when does non-collapse correspond to the welfare maximization solution? It is commonly held that fishing collapse is a public bad (Berck, 1979). We argue that a clear answer requires an explicit discussion of the welfare model under evaluation. This chapter discusses welfare functions and technological factors (cost, production, and biological growth functions) which condition the answer to this question. Under some particular conditions, fishing collapse can correspond to the welfare optimal solution.

Second, when does fishing collapse occur in actual fisheries? Economic collapse of industrial marine fisheries is not a so uncommon phenomenon. We cite several historical examples. In order to understand the origins and likelihood of this problem, we discuss the necessity and/or sufficiency of different conditions that the fishery literature has traditionally associated with the occurrence of fishing collapses. Institutional factors (access schemes, firms' harvesting competition strategies) and technological conditions (cost, production, and biological growth functions) are considered from a survey oriented perspective.

The technological side of the problem is analysed with greater detail[1]. We analyse harvesting incentives stemming from: (i) increasing biological growth returns for low population levels, and (ii) indivisible and highly specific harvesting capacity which presumably reinforces (according to 'folk' propositions) private incentives to allow for a fishing collapse. Both factors are commonly held to be important triggering forces leading to collapse.

We first argue that factor (i) is neither a necessary nor a sufficient condition for fishing collapse. This implies that the possibility of a fishing collapse is more widely ranged than otherwise expected. In terms of factor (ii), we argue that the 'folk' proposition must be conditioned by the nature of the fixed costs which emerge from the indivisibilities in harvesting capacity. A key aspect is how costly it is for individual firms to reduce fishing efforts, even when low harvesting performances, at overdepleted fisk stock levels, create incentives to do so. The discussion differentiates between *quasi* fixed costs which can be avoided if harvesting stops, and *re-entry* fixed costs which are triggered by the decision to stop harvesting operations with the intention to resume them later.

Quasi-fixed costs are expected to create incentives for intensive harvesting, given their impact in terms of decreasing average unit harvesting costs as harvest levels increase. The relative importance of re-entry costs determines whether these incentives for intensive harvesting result in *sustained* depletion, and hence in the promotion of a fishing collapse, or in *cyclical* harvesting strategies which can avoid collapse. As re-entry costs increase, harvesting indivisibilities (created by quasi-fixed factors) will tend to increase the likelihood of attaining a fishing collapse as the dominant outcome.

The discussion in this chapter is divided as follows. Section (2.B) briefly compares the economic and biological approaches to the long-run sustainability issue. Section (2.C) discusses basic concepts. Section (2.D) develops a welfare model used

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[1] Institutional factors are explored with more details in the following chapters.

as a yardstick in the analysis that follows. Section (2.E) discusses the necessity and/or sufficiency of different conditions that the literature on fisheries has traditionally associated with the occurrence of fishing collapses. Section (2.F) offers concluding remarks.

(2.B) Economists versus marine biologists.

Although sustainability ideas are deeply rooted in the economic profession[2] and currently enjoy a fashionable renewed popularity among economists, in the field of fishing regulation these ideas have been traditionally defended by marine biologists. Different emphasis and priorities, on sources of distortion and policy objectives, are likely to be found between economists and marine biologists when they consider fishing regulations.

Economists' analysis tends to concentrate on the incentive issues underlying the possibility of an inefficient dissipation of Ricardian rents. The traditional analysis focuses on the nonexistence of private property rights for fish stocks. After Coase (1960) the focus has been redirected to either the costs of *using* these property rights or the costs of transacting for their creation and enforcement. Then the analyst embraces propositions on harvesting firms' strategic interactions and the industry equilibria that can best describe the fishery under analysis.

In the economist's methodological view, there is usually a minor concern for instability and multiple equilibria issues. The emphasis and policy priorities are directed to the creation of property rights systems or substitutes for them. We then find propositions in favour of Pigouvian taxes or catch quotas devices. The corresponding methodological devices, enabling us to focus the analysis on these issues, are consistent with modelling definitions that usually consider strictly convex choice spaces; that is, the use of strictly concave preference functions and biological growth rules, along with the assumption of strictly convex cost functions (see Clark,

[2] For example, think of the influences of Malthusian and Ricardian theories.

1976; Gordon, 1954; Scott, 1955; Munro and Scott, 1985). This modelling framework allows us to rule out unwanted complications related to multiple equilibria issues and stability problems.

Marine biologists center their attention on long-run equilibrium issues, usually emphasizing the possibility of multiple equilibria and the related risks of achieving a collapse outcome, denoting at times an extinction concern and on occasions an economic closure concern (Idyll, 1973; Gulland, 1988). The modelling framework is specified to minimize complications related to the incentive structures that determine the choice options. We then encounter modelling definitions that consider very simple rules of firms' competition and industry equilibrium; for example, *ad hoc* assumptions on entry or investment functions and harvesting competition rules without strategic considerations (e.g., Smith, 1968; Beddington, Watts and Wright, 1975; Hoel, 1978; Berck, 1979; Hartwick, 1982).

The resulting emphasis from the biological perspective, though it considers incentive arguments due to the existence of common property, tends to focus on defining minimum population levels below which a fishing collapse can occur. The corresponding policy priorities concentrate on prescribing maximum permissible harvesting levels aimed at preventing overfishing outcomes. In this case the definition of overfishing is strongly biased towards biologically defined population targets.

It is easy to realize that these different visions and priorities can lead to different regulatory frameworks as optimal solutions. Marine biologists will emphasize long run sustainability objectives, demanding biologically oriented restrictions on catches. Economists will probably condition the previous demand on more exacting efficiency tests. These different professional perspectives, and the multiple potential sources of distortion and justification for fishing regulations, have produced ambiguities in concept definitions and causality arguments that underlie the justifications for regulatory actions. In order to improve the scientific contribution to the debate on fishing regulations, additional efforts are required in terms of refining the related concept definitions and causality arguments.

(2.C) Basic concepts.

Since the early 1950s there has been a tendency in favour of regulating industrial fisheries. This was mainly based on the proposition that fish stocks would not only be inefficiently depleted, given the absence of enforceable property rights, but also face risks of economic collapse or even of biological extinction.

We already know, from accumulated empirical evidence, that these concerns correctly anticipated the economic collapse of several marine industrial fisheries during the second half of XXth century. We can cite several historical examples of the economic collapse of pelagic fisheries[3]: the collapse of the Japanese sardine industry in the early 1940s; of the Californian sardine fishery in the early 1950s; of the North Sea herring stocks in the late 1960s and early 1970s, and the collapse of the Peruvian anchovy fishery in 1972-73 [4].

This evidence, however, does not imply a definite justification for regulation of industrial fisheries. A rigorous defense of fishing regulations should: (i) identify the conditions under which the undesired outcomes occur, (ii) differentiate between the necessity and sufficiency of those conditions, and (iii) argue why the undesired outcome represents a *net* welfare worsening result.

A non-trivial part of these requirements is to specify as precisely as possible what is meant by the different concepts used in arguments and propositions for

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[3] Most of the XX century collapsed fisheries correspond to pelagic fish species which are used by fish meal industries. *Pelagic* fish species (such as sardines, anchovies and herrings) tend to be stocks highly variable and difficult to assess and manage. This is related to the fact that pelagic species are usually shorter lived and faster growing in comparison to other important fish species (e.g., demersal). Therefore, they are more exposed to recruitment fluctuations. And *recruits* in these fish populations tend to show high variability due to environmental shocks (Gulland, 1988, ch. 11).

[4] See Idyll (1973) for the specific case of the Peruvian anchovy; also see Gulland (1988) and Cushing (1988) for comparative historical analyses of different marine fisheries.

regulation. In what follows we discuss three important concepts: (1) long run sustainability and fishing collapse, (2) equilibrium and stability definitions, and (3) related welfare prescriptions.

(2.C.1) Long-run sustainability.

Let us use the term *system* to denote the fish population that is subject to economic depletion. More precisely, let us denote the *system* the following function:

$$\begin{aligned} \dot{x}(t) &= S\big(x(t);\alpha\big) \\ x(0) &= x_0 \end{aligned} \tag{1}$$

where x(t) denotes the state-variable vector at continuous time t of this dynamic system, $\dot{x}$ its time derivative, x_0 the initial state, and α a parameter vector that can affect the rule of dynamic motion for x. For instance, in a simple case state x can represent the population level of a homogeneous single fish species, whereas α may represents its exogenous rate of natural growth.

By abstracting from details and concentrating on essentials, we can think of the sustainability argument as a defense for regulation based on the aim of preserving the economic or biological survival of the system. In the first case, the argument refers to preventing the *economic collapse* (closure) of the fishing industry that exploits the fish population x. In the second, it refers to preventing the *extinction* of the biological population. By *economic collapse* we mean a long run industry equilibrium with a sufficiently low fish stock level such that the industry's average variable costs are high enough to make it unprofitable, for a sufficiently high percentage of firms in the industry, to continue with positive harvesting operations in that fishery. A case with no catches from the fishing grounds can obviously be considered as a fishery under economic collapse. However, our interpretation of economic collapse also includes cases of fishing grounds with positive but sufficiently low aggregate harvesting outputs such that undesired welfare effects are triggered by those output levels; for example, undesired regional unemployment effects.

Clearly extinction implies collapse, but not vice versa. Accordingly, these two concepts can have quite different welfare consequences. Moreover, the definition of each of them is not a trivial task. Each of them can represent a complex set of circumstances. For instance, when we talk about *extinction* what do we really refer to? Is it the *full* biological disappearance of a species? What definition of geographical space is considered by this disappearance proposition? Is it within a given region? Within a country or the whole world? How do these different geographical definitions affect the welfare consequences of identifying local versus global species extinction? Which technological set conditions the disappearance proposition? It would not be difficult to add new questions and doubts. A similar process would occur if we start thinking more carefully about the definition of *economic closure*. Nonetheless, we will not pursue this type of analysis.

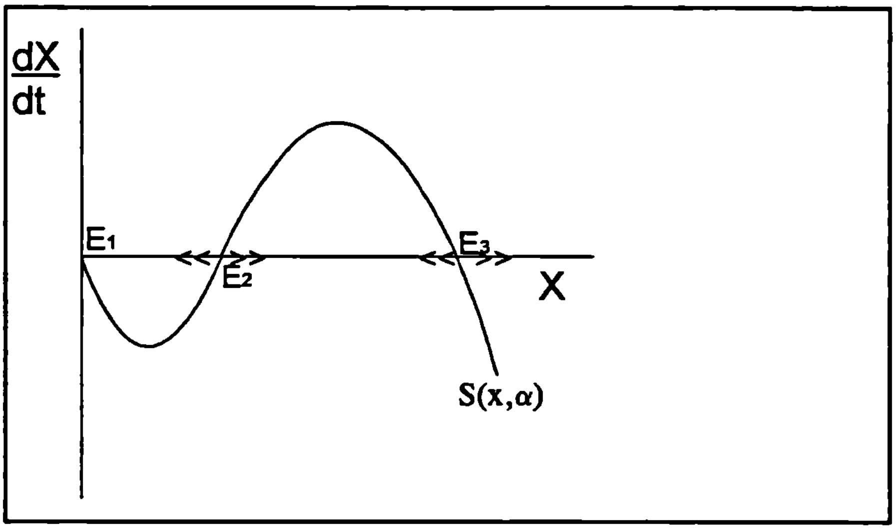
Our discussion makes no distinction between economic closure and biological extinction. It suffices for our purposes to define a *minimum* x-level x_m below which the regulator aims not to be. Call this unwanted x range a *fishing collapse* outcome; where fishing collapse can be understood either as economic closure or biological extinction.

To make the definition of x_m more precise it would be necessary to make explicit the welfare optimization model under analysis. At this stage we are not going to pursue this exercise. Instead, by a sustainability target we mean the regulator's desire to prevent a fishing collapse outcome.

(2.C.2) Multiple equilibria.

The sustainability argument is based on the proposition that industrial fisheries can be best described by a function $\dot{x}=S(x(t))$ that represents a dynamic system with multiple equilibria. The simplest case is where $\dot{x}=S(x(t))$ has three stationary equilibria with two of them locally stable for a given neighbourhood. We illustrate this in Figure 2.1. The vertical axis measures the derivative of x with respect to t and the horizontal axis the level of x. Points E_1 and E_3 represent two locally stable fixed points. In this case, the collapse outcome is represented by the lowest stationary equilibrium E_1. However, for a regulator that aims to avoid outcome E_1 the unwanted x-range is defined by x levels below the minimum point $x_m = E_2$.

Figure 2.1



The dynamic nature of the system could be better characterized by more complex long-run equilibrium concepts than the traditional stationary points or long-run steady states. It would suffice to increase the degree of non-linearity in the dynamic rule of motion of system S(x), even ruling out completely the existence of random shocks, in order to obtain increasingly more complex types of long-run temporal trajectories for x[5]. This would make it necessary to refine the definition for equilibrium state. A relatively close concept to stationary equilibria is the idea of dynamic systems which are better characterized by different types of bounded and periodic temporal trajectories. The (two period) limit cycle solution for the Lotka-

[5] See footnote 7 for reference sources.

Volterra model of a predator-prey species fishery is a classic example of a periodic solution set which is an equilibrium for a dynamic system (Clark, 1976).

Periodicity in the observation of alternating states allows us to use a concept of equilibrium whereby *bounded* fluctuations allow us to rescue a concept of stability for these periodic trajectories[6]. As we move away from the stationary idea of equilibrium, local stability for specific fixed points loses ground. However, bounded periodicity allows us to define different concepts of *structural* stability for dynamic systems. As we move away from the relevance of stationary equilibria, the concept of equilibrium redirects its focus towards *convergence* processes to some well-defined set of points within the feasible x-space[7].

The concept of structural stability weakens as the temporal trajectories of S(x) become aperiodic and also more and more dependent on the starting position of the system. In the limit, the trajectories may become completely *chaotic*[8].

The key issue is that sustainability arguments usually presuppose dynamic systems with multiple equilibria. Therefore, the analyst should be careful to clarify the type of dynamic equilibria that he is referring to. That definition is crucial in

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[6] The idea of using 'bounded periodicity' to define different equilibrium concepts has a well-established tradition within the mathematics of non-linear dynamic systems (see, for example, Azaríades, 1993).

[7] In fact, non-linear dynamics conceptualizes long-run equilibria by the general concept of *attractor*. Intuitively defined, it refers to the set of points to which the dynamic path of x converges as the time horizon tends to infinite. The simplest type of an attractor is a stationary fixed point. Then bounded periodic temporal solutions come. They are usually denoted by 'orbits'. As the nature of the dynamic trajectories becomes more complex, we think of moving from one type of attractor to another. The system will move from one attractor to another when the *qualitative* nature of the dynamic solutions change. The theory denotes these stages of qualitative changes by 'bifurcation' processes. In the limit case of 'chaotic' trajectories we speak of 'strange attractors'. For more details and original references see Azariades(1993), Benhabib (1992), Baumol and Benhabib (1989), Scheinkman (1990) and Bullard and Butler (1993). Also the book by Goodwin (1990).

[8] That is, when the system shows "infinitely many periodic orbits of arbitrary long period as well as completely aperiodic trajectories that never return to any point visited previously" (Azariades, 1993, p.106).

order to understand and analyse the dynamic properties (alternative equilibria, convergent processes, relevant neighbourhoods) of the system under evaluation.

(2.C.3) Welfare prescriptions.

Sustainability targets, proposing fishing regulations to prevent a fishing collapse, must argue that the collapse outcome represents a net welfare worsening result. If collapse is meant to imply extinction, the 'folk' basic argument is that we will be permanently losing some valuable[9] genetic biological information. A key aspect of this argument is the idea of *permanent* losses. Underlying it, we encounter the concept of irreversibility costs.

Arrow (1968) was one of the first to define *irreversibility* in a precise manner. Within a deterministic capital accumulation problem, he defined this concept as implying a non-negative investment constraint. More recent discussions tend to model this concept by the more general device of introducing cost asymmetries between upward and downward capital adjustment decisions (Pindyck, 1991). The concept of sunk costs belongs to this line of thought[10]. The intuition behind irreversibility costs is clear: it refers to dynamic (investment) decisions that involve highly specific capital assets such that, once investment resources are committed to them, their opportunity cost decreases significantly with respect to their replacement value.

The idea of irreversible investment decisions, along with the proposition of uncertain future values for the corresponding capital stocks, have triggered since the mid 1970s an increasing literature on environmental preservation issues and the

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[9] The concept of valuable can represent an 'option value'. Weisbrod (1964) was a pioneering paper arguing the option value of current consumption when there exists uncertainty with respect to its future value. Extensions of this idea to the topics of "environmental preservation" can be found in Fisher, Krutilla and Cicchetti (1972), Arrow and Fisher (1974), Henry (1974), and more recently Weitzman (1992). Similar applications to the problem of uncertain and irreversible investment decisions are found in Bernanke (1983), Brennan and Schwartz (1985) and Pindyck (1991).

[10] Sunk costs imply a positive difference between the replacement cost and the resale price of a given capital stock.

opportunity costs represented by the possibility of losing option values[11]. It is this interpretation of irreversibility effects that underlies the 'folk' extinction proposition referring to permanent losses. This proposition argues that once an extinction outcome is achieved, society loses the option to backtrack, if it wanted to, to any *ex post* desired previous position.

However, to propose the existence of irreversibility costs, due to the occurrence of a fishing collapse, is not a *sufficient* condition to prove the optimality of preventing that outcome through regulation. The irreversibility argument only corresponds to an opportunity cost. That means that we, as a society, lose 'something valuable' if the irreversible outcome occurs. However, there surely are private benefits from the actions leading to that outcome. Where then must the net balance be placed by the welfare yardstick? We need an explicit welfare model to provide an answer. This exercise does not seem to have an *a priori* answer.

Would our previous analysis have changed if we had defined the collapse outcome as economic closure, instead of biological extinction? Yes, in some of the details and definitions that we have made, but not in the essentials.

Loosely defined, economic closure is meant to imply that a 'sufficiently high' percentage of firms in the industry have to shutdown for a 'sufficiently long' period. The relevant welfare model should clarify what is understood by 'sufficiently high' and 'sufficiently long'. This is not relevant to our purposes here. What really matters is that again we have a proposition arguing for some type of 'exit cost' function.

For example, some informal ('folk') arguments propose that the economic closure of fishing industries is a welfare worsening outcome because once fish stocks

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[11] This literature considers the basic 'learning option' proposition that it may be better (in a welfare sense) "to wait when we are unsure about future values" [Arrow and Fisher(1974]. However, it is far from clear that the combination of uncertain future values and current irreversible investment decisions lead to unambiguous welfare prescriptions in the sense of "better to wait" or "better to postpone current production". Sequential investment models can yield the opposite prescription: Roberts and Weitzman(1981) is an example where the investment process yields information about the uncertain future values (for instance, think of the discovery and value assessment processes in the oil extraction industry).

achieve a high level of overdepletion and firms shutdown, the high specificity of remaining capital stocks will be an obstacle to profitable substitution and factor movements to other production processes, dooming that geographical location to languish through prolonged inactivity. Whether or not this is true, is indeed, an empirical issue. This means that we need to compare costs and benefits for different people, at different times, and then argue for a 'net balance' or welfare answer. This is precisely our previous point.

(2.D) A welfare model for optimal harvesting.

This section presents a simple welfare model for the optimal depletion of a renewable natural resource. The modelling structure summarizes the essentials of the traditional (textbook) model that is used in discussing the optimal depletion of fish stocks. The point to be highlighted will be that this modelling strategy assigns a minor concern to the analysis of fishing collapse outcomes. Instead, it concentrates on the analysis of an intertemporal arbitrage condition describing a positive long-run stationary steady state for fish stocks. We will use this welfare model as a yardstick to examine the arguments that follow.

Suppose at this stage that there is a single decision maker, say a social planner, who is the sole owner of resource x and whose objective function is the maximization of the total discounted net economic benefits derived from depleting x. Suppose that this optimization program considers an infinite time horizon. Assume that the only choice variable corresponds to the harvesting rate h(t) indexed for time t. Imagine that the choice problem occurs in a fully deterministic setting.

The sole owner assumption is meant to imply that the planner's problem is defined independently from the ownership of the natural resource. We assume that the planner has full control over the harvesting of the fish stock. Therefore, the planner's optimization problem can be expressed as follows:

$$\underset{h(t)}{Max}\ V=\int_0^{\infty} e^{-\delta t}\,\Pi(x(t),h(t))\ dt \tag{2}$$

subject to:

$$G(x,\ h)\ =\ \frac{dx}{dt}\ =\ F(x)-h(t)$$
$$x(t)\geq 0,\ h(t)\geq 0,\ x(0)=x_0 \tag{3}$$

where V is the present value of the current and future net benefit streams that accrue from the resource depletion; with $\Pi(x,h)$ as the flow of net economic benefits, x(t) as the resource stock, h(t) as the harvest rate and δ the relevant social discount rate. The social planner's benefit function Π may represent the social utility accruing from the resource consumption flows, or a profit function if we think of the social planner as a sole owner firm[12]. In our analysis we consider the latter option. Therefore, $\Pi(x,h)$ denotes the Ricardian rents that accrue from the depletion rate h(t) of natural resource x(t).

The constraint for the problem arises from the net biological growth of x which is denoted by G(x,h), where F(x) represents the natural growth rate of x, such that $x(t)\geq 0$ and $h(t)\geq 0$[13].

The solution to problem (2)-(3) can be found by maximizing, for all t, the following current-valued Hamiltonian:

$$\max_{h}\ H=\Pi(x,h)+\lambda[F(x)-h] \tag{4}$$

where λ is the current valued scarcity value of x.

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[12] The profit function can be a measure of welfare if we assume *inter alia* that prices are taken as given.

[13] Note that we have excluded capacity constraints on the choice of h(t). This rules out a possible source of non-convexities in the choice problem (if the capacity constraint is binding at the optimal h(t)); consequently, this assumption also eliminates a potential source of multiple equilibria outcomes.

By imposing the assumption of strict convexity on this problem's choice space, i.e., when both functions G(x,h) and Π(x,h) are *(jointly) strictly concave* in the state variable x(t) and the control variable h(t), we know that the following first-order conditions suffice to identify a trajectory pair (h^*, x^*) which maximize function V subject to (3):[14]

$$[\frac{\partial H}{\partial h}]h^*=0\ ;\ for\ h^*>0,\ then\ [\frac{\partial H}{\partial h}]=0\ \Rightarrow\frac{\partial \Pi}{\partial h}=\lambda \tag{5}$$

$$\dot{x}=\frac{\partial H^*}{\partial \lambda};\ with\ H^*=H(h^*)\ \ such\ that\ \dot{x}=F(x)-h^* \tag{6}$$

$$\dot{\lambda}=\delta\lambda-\frac{\partial H^*}{\partial x}\ =\ \delta\lambda-\frac{\partial \Pi^*(h^*)}{\partial x}-\lambda F'(x) \tag{7}$$

$$\lim_{t\to\infty}\ [\lambda(t)\ e^{-\delta t}]\ x(t)=0 \tag{8}$$

The simultaneous fulfilment of (i) the previous (joint) strict concavity condition, and (ii) the transversality condition in (8), ensures that the optimal trajectories will converge to a steady state in which the harvest rate and the fish stock are constant (Chiang, 1992, p.124). This implies $\dot{x}=0$, $\dot{\lambda}=0$; hence, by introducing (5) into (7) and then combining it with (6), we obtain the following equation that characterizes the steady state solution pair (x^*,h^*):

[14]Strict joint concavity requires that $[H_{hh}H_{xx} - H_{xh}\ H_{hx}] > 0$. The uniqueness of the maximum solution (h^*, x^*) is assured if G(x,h) and Π(x,h) are (jointly) *strictly* concave *everywhere* in the feasible choice space for x and h. [For more details, see Chiang, 1992, chapter 4.2]

$$F'(x^*) + \frac{\partial\Pi/\partial x^*}{\partial\Pi/\partial h}\Big|_{h=F(x^*)} = \delta \tag{9}$$

where F'(x) denotes the derivative of function F with respect to stock x.

This result is known in the literature as "the fundamental rule of renewable resource depletion" (Pearce and Turner, 1990, ch.16). This condition describes the long-run stationary equilibrium for system (2)-(3), which is represented by the stationary state x^*, such that $F(x^*)=h^*$, at which net capital gains are zero. In order to assure that x^* is positive, it must be true that the left-hand side of equation (9), when the partial derivatives are evaluated at $x=0$, is greater than the discount rate δ. We will take up this issue again in the next section (2.E).

The left-hand side of equation (9) is the marginal sustainable resource rent that results from an additional unit of investment in x(t), divided by the cost of that investment which is the foregone rent from current harvesting h[15]. This gives a rate of return for investments in x, which has to be equal to δ in equilibrium in order to have zero capital gains in terms of present value.

This rate of return is composed of two factors: first, the "instantaneous marginal product" of the resource, F'(x). This is a direct productivity effect from marginal changes in x over the profit function. Second, in fishery models it is usually assumed that $\partial\Pi(x,.)/\partial x>0$, presumably because the unit cost of harvesting decreases, the higher the stock level x is. In this case, to postpone harvests today and hence make the resource more abundant and less costly to exploit, adds a marginal benefit to the marginal growth F'(x). This additional effect has been traditionally called the 'marginal stock' or 'user cost' effect in the literature on fisheries.

[15] To illustrate this reading, let us suppose that function Π is linear in h, with a margin per unit of harvest equal to (p- c(x)), with c(x) as the unit cost of harvesting. In this case, we can see that equation (9) corresponds to:

$$\frac{\partial[(p-c(x^*))F(x^*)]\ /\partial x^*}{p-c(x^*)} = \delta \tag{10}$$

How is the long-run optimal steady state x^* arrived at in this model? Suppose that the profit function $\Pi(x,h)$ were linear in the harvest rate $h(t)$, as the (textbook) fishery models normally assume. Due to this linearity assumption, the optimal approaching path to x^* is a very simple one: the Most Rapid Approaching Path (MRAP) or 'bang-bang' solution; that is, whenever $\partial H/\partial h<0$ then set $h=0$ (where H is the Hamiltonian function described by equation (4)); otherwise, if $\partial H/\partial h>0$ then set $h=h^*$ such that the fish stock is *instantaneously* driven to its equilibrium steady state level x^*.

Owing to the linearity assumption, the decision maker always obtains a constant unit margin per additional unit of h. Consequently, the optimizing agent has no 'scale sensitive' penalties for rapid resource investment or disinvestment decisions. Therefore, the control variable $h(t)$ fully adjusts to accommodate the desired state x^*.

We can incorporate scale related harvesting costs into the analysis by assuming that the benefit function is *strictly* concave in h, that is $\partial\Pi/\partial h>0$ and $\partial^2\Pi/\partial h^2<0$.[16] In this case, the optimal approaching path is no longer the MRAP. Instead, the optimal path becomes now an *asymptotic* approaching path to the long-run equilibrium vector (h^*,x^*); with this approaching path increasing or decreasing depending on the initial state $x(0)$ (see Wilen, 1985).

Therefore, the analysis for the management of a renewable resource within a convex choice world seems to be clear: we set the conditions for the existence and uniqueness of a long-run optimal stationary equilibrium for the fish stock, and then

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[16] This is consistent with the presence of decreasing returns in h or the effect of strictly convex harvesting costs. The introduction of strict convexity into the (investment) cost function is the traditional device that neoclassical investment theory has used to model asymptotic adjustment paths to the desired long-run capital stocks. (Takayama, 1985, ch. 8.E). Non-convex adjustment costs, for example due to irreversible investments, make it possible to model more complicated dynamic adjustment paths.

we prove its stability properties (hopefully, global stability)[17]. In this stationary solution, the stock x^* is held constant by continuously harvesting the resource's natural growth ($h^*=F(x^*)$). As a consequence, along with this steady state x^* we obtain a stable (*sustainable*) harvest rate h^*. Whenever the initial stock is greater than the optimal stationary level, the stock is harvested at a rate greater than its natural rate of growth, and vice versa, in order to attain the desired long-run stationary stock level.

This standard methodology has had a strong appeal on the way we think of resource (or, in general, dynamic optimization) problems as choices between stable long-run equilibria, with corresponding stable (sustainable) control variables, such as the concept of maximum sustainable yield (MSY) that we frequently encounter in fishery management discussions (see chapter 3). This thinking style undoubtedly acquires more life and self-convincing power as we move closer to discussions on policy implementation issues, given the costs of implementing state adjustable harvesting controls. As a consequence, explicit analyses of dynamic approaching paths remain as peripheral issues[18].

There are clear methodological advantages in the tendency to rely on convex or strictly convex choice spaces when we want to analyse dynamic optimization problems. We can focus on conditions that describe unique, stable and positive long-run equilibrium states. However, this modelling strategy neglects some important

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[17] By imposing the required curvature conditions we can develop comparative dynamic analyses, comparing the resulting equilibria for different parametric configurations. The origin of this method comes from Samuelson (1947) whose 'correspondence principle' argues that comparative static means nothing without a corresponding statement for the stability properties of the model.

[18] It must be said, however, that since the early 1980s methodological advances have taken place in the analysis of dynamic optimization programs. These advances have been originating more general frameworks and more powerful tools for dynamic analyses. Resource economics has contributed to this result, as has the revival of (endogenous) growth theories. The reshaping that has taken place, and is still taking place, in the field of dynamic macroeconomics, triggered by the works of Lucas, Sargent and Wallace, has also contributed, probably with greater importance, to the above mentioned methodological progress. It is illuminating to read the perception of Lucas himself on this process. See the introduction to his lectures on business cycles (Lucas, 1987).

features of the fishery management problem. First, it puts only minor emphasis on multiple equilibria analyses and the corresponding discussions on instability issues, among them the risk of fishing collapse. Second, in 'unique and stationary equilibrium' models we encounter either no dynamic considerations at all (i.e., *bang bang* solutions) or, if they are not completely absent, the models capture them by simple asymptotic solution paths. Both alternatives imply neglecting the analysis of economically meaningful dynamic trade-offs (for instance, cyclical versus more stable harvesting) for the choice variable(s) under evaluation.

As a consequence, this modelling strategy has promoted a 'folk' or 'policy oriented' wisdom that conceptualizes desired equilibrium states as stable stationary solutions which define stable 'long-run sustainable' harvesting policies. Despite the fact that industrial fisheries tend to show a quite different situation (cyclical harvesting), this folk wisdom has tended to promote regulatory actions that help to obtain more stable harvesting temporal performances. 'Unstable' (cyclical) harvesting paths are then usually perceived as undesired, inefficient and disequilibrium phenomena[19].

As far as we have seen in this section, instability issues have not come yet into scene. Harvests, stocks and economic rents[20] are all modelled as positive and constant, all of them being consistent with the unique and stable long-run steady state equilibrium which arises from the assumptions that ensure strict convexity for the choice space. This is what we called, in the introduction to this section, a 'minor concern' in the analysis of fishing collapses. Let us turn back to the latter issue.

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[19] We took the inspiration for this interpretation from Lucas's writings on business cycles (see, for example, Lucas, 1981, in particular papers No. 11, 1977 and No. 15, 1980).

[20] The latter feature is derived from the sole ownership assumption.

(2.E) On the possibility of fishing collapse.

This section analyses conditions under which a fishing collapse can occur. It focuses on discussing the necessity and/or sufficiency of alternative conditions that the fishery literature has traditionally associated with the occurrence of collapse outcomes. This analysis excludes welfare considerations.

Three important limitations in our analysis must be clarified from the outset. Each of them refers to factors that can affect the triggering and propagating incentive mechanisms that promote the occurrence of fishing collapses. First, we do not analyse strategic interactions, between harvesting firms, that can arise from the existence of common property. Hence, we bypass a formal analysis of the harvesting equilibria which emerge from alternative hypotheses for the solution to the non-cooperative harvesting game arising from commonality[21]. The latter issue is studied in chapters 5 and 6.

Second, we exclude formal arguments related to the issue of uncertain fish stock levels and their composition. Hence, we abstract from collapse explanations based on the costly monitoring of fish stocks and the effects from *persistent* random shocks. Both elements can be used to justify the occurrence of a locally stable collapse outcome. For both of them there exists some support from empirical evidence[22].

Third, we will abstract from species interactions among different fish stock populations. Instead, we concentrate on discussing a single-species fishery[23].

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[21] Clemhout, Wan (1985a; 1986) are two papers that attempt to link the analysis of fishing collapses (understood as extinction in both cases) with basic hypotheses for Nash non-cooperative harvesting. While the 1985 paper does so within a deterministic setting, the 1986 paper considers a random hazard of extinction whose probability of occurrence can be affected by the solution to the non-cooperative harvesting game.

[22] Reference sources on fisheries and uncertainty can be found in Clark, Munro and Charles(1985), Munro and Scott (1985), and Lewis (1982).

[23] For a recent model on multiple-species fisheries see Fischer and Mirman(1992). However, this paper does not deal with the collapse or extinction issue.

Nevertheless, though we realize the limitations, we resort to these simplifications to focus on collapse arguments that emphasize the combined effects from: (i) non-concavities in the natural growth function F(x), and (ii) non-concavities in the harvesting technology h(.).

We follow this approach because we aim to clarify some ambiguities that tend to arise in policy implementation discussions when they refer to the fishing collapse problem. Before going into details, let us explore, for comparative purposes, the incentive structure that can lead to a fishing collapse within a strictly convex choice world.

(2.E.1) Collapse within a convex choice space.

(2.E.1.a) The sole owner model.

Let us again address the sole ownership choice problem described by equations (2)-(3). Given joint strict concavity in h and x of this maximization problem, we know that equation (9) describes a unique stationary long-run equilibrium x-level denoted by x^*. By direct inspection of this equilibrium condition we can deduce that x^* will be lower, the higher the discount rate δ is[24].

For fish species with 'sufficiently low' growth rates F'(x), especially for small x[25], and where the function $\Pi(x,h)$ is either (i) 'relatively insensitive' to marginal changes in x (for example, low x-sensitivity of marginal harvesting costs), or (ii) $\Pi(x,h)$ has a 'relatively high' and positive sensitivity to additional units of h (for example, given a 'high' and positive current harvesting margin), we can expect that the higher the relevant discount rate, the higher the possibility that $x^*=0$ will be the long-run optimal steady state.

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[24] Recall that we must evaluate the functions' value at the steady state vector (x^*, h^*).

[25] Near the critical x-level x_m that triggers the definition of fishing collapse.

This means, given the above referred conditions, that the intertemporal arbitrage (equilibrium) condition that rules the investment decisions in x can prescribe that, in terms of present value, it is *optimal* for our sole owner decision maker to allow for collapse. This implies that fishing collapse could be, under some particular conditions, the welfare optimal solution. Clark (1973) offers a discrete time model in this line of arguments.

(2.E.1.b) Open access commonality.

Common property with open access is usually interpreted as leading to *stock myopic* harvesting strategies, where myopic harvesting means that firms will not internalize the opportunity cost of extracting an additional unit of fish stock (see chapter 6). This is not an obvious proposition[26]. However, let us suppose that 'high' costs of excluding rivals' harvesting lead to a stock myopic harvesting competition that inefficiently dissipates the natural resource's rents.

Following the myopia argument, the traditional literature on fisheries has suggested that the allocative effect of open access commonality with multiple harvesting firms is *analogous* to an infinite discount rate for the case of a sole owner harvester (Scott, 1955 and Clark, 1976, chapter 2.5); in the sense that, in both cases, the future state of the system under depletion has no implications for current harvesting decisions.

This line of argument then proposes that such incentive structure could eventually lead to the collapse of the fishery. The point to be stressed here is that 'open access commonality' is not a *sufficient* condition by itself to bring about a collapse outcome. And it *may or may not* be a necessary condition, depending on the explicit modelling structure under analysis.

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[26] Negligible transaction costs, in allowing and enforcing the exclusive use of units of x, could allow the emergence of Coasian contracts aimed at avoiding the inefficient dissipation of Ricardian rents. This idea is valid with or without formal private property rights.

In order to validate the collapse corollary within the myopic harvesting proposition, we need to assume that the industry as a whole still faces positive profit margins per unit of marginal harvesting when the fishery arrives at the critical x_m that triggers the local stability of the x-range (or x-level) that is associated with fishing collapse. This additional condition of positive profit margins when $x \rightarrow x_m$ is not an obvious assumption. Think of the possibility of increasing marginal harvesting costs as the stock x falls. If this were the case, harvesting firms would have incentives to reduce their catches as stock x falls. If marginal harvesting costs were sufficiently sensitive with respect to decreasing x levels, the open access equilibrium could imply long-run equilibrium levels for stock x above its critical value x_m.

However, by combining open access commonality with 'strong' profit incentives for intensive and continued current harvesting, it is possible to obtain a plausible explanation for the occurrence of some fishing collapse experiences. For instance, the collapse of the Blue Whale international fishery: the combination between a 'low' growth function $F'(x)$ with respect to the obtainable current profit margin per unit of harvesting, and the existence of a *de facto* open access commonality are generally thought to have led to collapse. Similar arguments have been used to explain the economic collapse of several pelagic industrial fisheries. In the latter case a special emphasis is put on the effect of falling average harvesting costs that result from defensive strategies that these fish species follow at reduced population levels[27].

(2.E.2) Collapse with non-concavities in the natural growth function.

Several models that discuss fishing collapse problems are based on natural growth functions $F(x)=dx/dt$ that do not exhibit strict concavity. This helps to model the

[27] As the fish stock becomes smaller, individuals tend to increase their (density) concentration as a defensive response to natural predators. For species that live near the surface, like pelagic fish, this tends to reduce the fleet's harvesting costs.

possibility of multiple steady state equilibria with local stability. By introducing a non-concavity in F(x) for low x-values we can generate local stability for a steady state solution such that $x \to 0$, given a prespecified neighbourhood with boundaries such that $0 \leq x \leq x_m$ (see, for example, Lewis and Schmalensee, 1982; and Levhari, Michener and Mirman, 1982).

The feature of initial non-concavity in F(x) usually aims to model the presence of increasing biological growth returns for low population levels; that is, that the proportional growth rate $r(x) = [dx/dt]/x$ initially be an increasing function of x for low x levels. However, this is not always a *necessary* condition to obtain the local stability of a collapse outcome. For the case of a *strictly concave* natural growth function $F(x) = dx/dt$, with $F(x) > 0$ for all $x > 0$, we could model an initial region of negative *net growth* (natural growth minus total catches), by simply considering a *constant* positive rate of harvesting (independent of x values). The region of x values with negative net growth would imply local stability for the steady state equilibrium $x = 0$. Some models resort to this option (see, for example, Mirman and Spulber, 1984).

Models that consider non-concavities in F(x) normally work with harvesting functions which are linear in stock x[28]. In the case of linear harvesting technologies, the use of strictly concave functions F(x) would allow to obtain only one stable steady state equilibrium, either positive or equal to zero (full depletion). The feature of initial non-concavity in F(x) helps to model more interesting (multiple equilibria) solutions, with at least two steady state equilibria showing local stability.

The models referred to in this section use either one of the following two types of local non-concavities in the natural growth function F(x). Following Clark (1976, ch.1) and Lewis and Schmalensee (1982), the first type is known as

[28] These functions are of the type $h = qzx$, with h as the harvest rate, q as a constant productivity parameter, z denoting fishing effort and x as the fish stock. This technology corresponds to the well-known Schaefer production function within fishery economics (see Clark, 1976, chapter 2).

depensation growth: it arises if the proportional growth rate $r(x)=F(x)/x$ is an *increasing* function of x for a given range of low x values (see Figure 2.2). The main effect that stems from these initial increasing returns in biological productivity consists in defining a critical harvesting level h^c (equal to the maximum proportional growth rate $r(x)$) above which population x is always driven towards extinction. For linear harvesting rates h such that $0<h<h^c$, like h_1 in Figure 2.2, we obtain a positive and locally stable steady state x_2 and the unstable steady state equilibrium x_1. If the initial stock level is above x_1, the harvest rate h_1 will drive the population to the positive equilibrium x_2. If the initial stock is below x_1, the population is driven to extinction[29]. For more formal details see, for example, Clark (1971).

A second type is usually modelled as implying $F(x)<0$ for a given range of low x values, in the vicinity of $x=0$ (see Figure 2.3). This case is known as *critical* depensation growth (Clark, 1976). It exhibits all of the features mentioned above for the first type but also an additional phenomenon: it defines a critical (*minimum viable*) population level x^c, with $F(x^c)=0$, such that if x falls below x^c then an *irreversible* process begins such that necessarily $x \to 0$, even without harvesting. As with the previous type of depensatory effects, any positive linear harvest rate, like h_2 in Figure 2.3, gives rise to two equilibria, x_1 and x_2, the former being unstable while the latter locally stable. For initial stock levels below x_1-type equilibrium, any positive harvest rate will drive the fish population to extinction[30].

Are these depensatory effects a sufficient condition for a collapse outcome? Are they a necessary condition? To both questions the answer is clearly no. First, in terms of the necessity issue, we have already seen that even within strictly convex

[29] In this case $x=0$ is also a locally stable steady state.

[30] We will keep the notation x^c to refer to *critical depensatory* effects. Notice in Figure 2.3 that x_1 corresponds to our previous notation x_m as the triggering x level of a locally stable collapse outcome.

Figure 2.2

Depensation growth

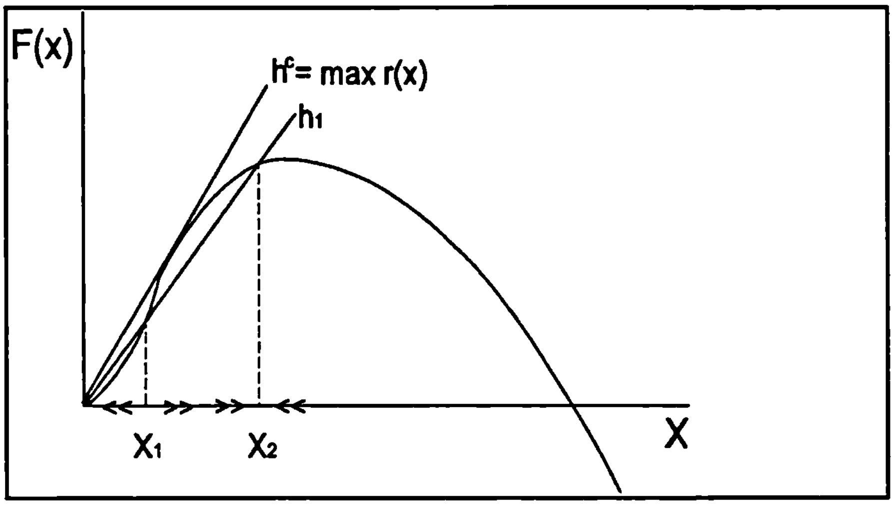
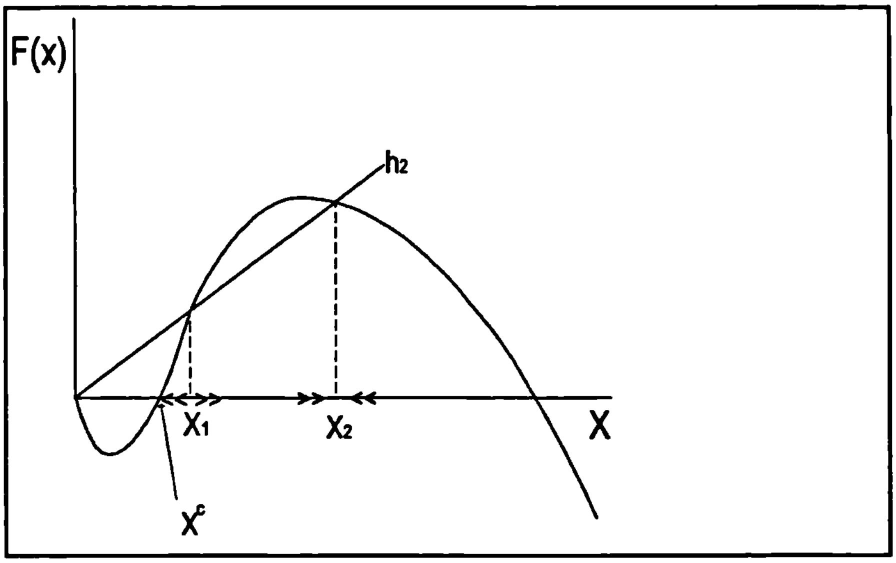


Figure 2.3

Critical depensation growth



choice problems we can argue for the possibility of a fishing collapse. Accordingly, depensatory effects in the biological growth function are not a strictly necessary condition to prove that x can collapse.

With respect to the sufficiency issue: when a *critical* depensation growth function exists, collapse inevitably occurs if x falls below x^c. In this case, even with zero harvesting, x would tend to collapse. An identical limit result ($x \to 0$) would occur with a *non-critical* depensatory growth function if the harvesting rate is located above the aforementioned critical harvesting level (h^c in Figure 2.2). However, in both cases the question that arises is: why would firms, who are fully aware of this risk, and presumably risk averse agents[31], not reduce, or even stop, their harvesting operations when they approximate the critical level x^c, or the critical harvesting level h^c for the case of non-critical depensation?

If we were to consider a sole owner case, as already discussed in section (2.E.1), the optimal fishing policy could be to allow for extinction. But then collapse would be explained by the arbitrage condition in equation (9). Hence, non-concavities in the natural growth function would be neither a sufficient nor a necessary condition for fishing collapse.

The question in the paragraph above surely loses interest when we think of *common pool* fisheries subject to *multiple* firm *non-cooperative* harvesting. In this case, even excluding problems of uncertainty on the true state of stock x, high costs of excluding rival firms' harvesting can help to explain why individual firms may intensively harvest the fish stock, to the extent that positive operating profit margins allow it, even if they are aware of the risk of fishing collapse. However, again in this case the non-concavity of function F(x) is not by itself a sufficient condition to explain the occurrence of fishing collapse.

[31] The probability of risk aversion presumably increases, the smaller the harvesting firms' size and the more specific (sunk) the capital stocks required in the harvesting technology.

Another important factor, frequently mentioned as a contributor to the occurrence of fishing collapses, is the existence of sunk harvesting capacity. This relates to arguments of costly downward adjustments for fishing efforts. We examine these ideas in what follows.

(2.E.3) Collapse due to non-convexities in the harvesting cost function.

Suppose that a single stock fishery is 'relatively near' to a critical x_m level such that x_m triggers the local stability of a collapse outcome. Define the collapse outcome as $x=0$. Assume that harvesting firms have perfect information on their relevant environment. The question to be addressed is: how the presence of harvesting indivisibilities can affect the incentives to reduce or stop depletion activities in order to avoid the triggering stock level x_m?

The 'folk' proposition under evaluation is that the existence of indivisible and highly specific harvesting capacity reinforces the incentives to approximate a collapse outcome. We argue that this proposition must be conditioned by the nature of the fixed costs arising from harvesting installed capacity.

We can think of two basic modelling options to address the effects from harvesting indivisibilities. First, we can define a harvesting technology $h=h(x,z,K)$ with x as the fish stock, z as the single variable input, call it *fishing effort*, which also corresponds to the single choice variable, and K as a fixed input which implies a cost $K>0$[32] which may or may not be avoidable if we set $h=0$. The fixed factor (cost) K introduces harvesting indivisibilities. Its presence generates increasing harvesting returns in the variable input z (a decreasing average cost per unit of z) as harvest levels increase and the corresponding equilibrium x level falls.

Following the series of papers by Lewis and Schmalensee (1977, 1979 and 1982, call them LS), our analysis differentiates between two types of cost K: (i) a

[32] In order to simplify notation, let us suppose that the price per unit of fixed factor is equal to 1. Hence K units of fixed factor imply a fixed cost of K monetary units.

quasi-fixed cost $Q>0$ that is required if $h>0$, but which is *avoidable* ($Q=0$) if the harvester shutdowns his operations ($h=0$)[33], and (ii) a fixed cost $R>0$ that is *triggered by* the decision to stop harvesting operations with the intention to resume them later. We can think of $R>0$ as an *ex post* 're-entry' fixed cost, or as an *ex ante* 'exit' cost previous to the shutdown decision[34].

The second modelling option would be to assume that the harvesting technology $h=h(x,y)$, with y denoting all other necessary inputs (in addition to x) for harvesting operations, has increasing returns to scale (IRS) for small x levels; that is, given an identical proportional change in x and y, the harvesting technology will show a more than proportional change in h levels. Again the result is that the choice variable (in this case h) has increasing returns in its operation as we move closer to low x levels, in the vicinity of the collapse outcome. This option is the standard way to deal with increasing returns when we want to analyse long-run equilibrium positions. We assume that all relevant input choices can be changed if we wish to do so[35].

In what follows we make explicit which modelling option is being considered by the analysis. Whatever be the case, the harvesting technology will be defined for a given harvesting firm. Unless stated otherwise, we will assume a fishing industry with price taking firms.

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[33] Think of $Q>0$ as fixed searching costs or lump sum wage payments to the fleet's crew.

[34] For example, $R>0$ can represent fixed costs that arise with temporary shutdown if the harvesting firm is vertically integrated with a processing plant. Imagine that an important cost in the latter stage corresponds to energy inputs. The standard technology for fish meal industries, for instance, implies that energy costs increase discontinuously, and initially above their operating mode level, after a temporary shutdown and the resumption of processing operations.

[35] However, economic intuition tells us that the proposition of IRS in $h(x,y)$ also needs to make use, although it does it implicitly, of an assumption about the presence of some indivisible factor in the relevant technology. Otherwise, how could we justify the more than proportional productivity of the variable input choices?

(2.E.3.a) Do increasing returns in harvesting prevent collapse?

There is a line of arguments that proposes that IRS in $h=h(x,y)$, at small x levels, can be a *sufficient* condition to avoid a collapse outcome such as $x^*=0$. Beddington, Watts and Wright (1975), henceforth BWW, is perhaps the best example[36]. Their basic (simplified) model considers: (1) a common pool renewable resource subject to closed entry, (2) multiple price-taking symmetric firms, each of them assumed to behave as a static profit optimizing harvester, (3) a strictly concave (logistic) growth function $F(x)$, (4) a harvesting cost function $C(h,x)= Ah^k x^{-\eta}$, with A as a positive constant, $\eta>0$, $k>1$ implying strict convexity of $C(h,.)$[37], and no fixed costs. Arguing that IRS in $h(x,y)$ is equivalent to imposing the condition $k-\eta<1$ on the cost function $C(x,h)$, and defining harvest rate h as the choice variable, BWW propose that the presence of IRS at small x levels is a *sufficient* condition to prevent collapse. Related to this, they argue that constant or decreasing returns to scale in harvesting is a *necessary* condition to achieve a collapse result.

The intuition that BWW offer to support their sufficiency proposition is that, at low x levels, harvesting firms will have incentives to increase stock x in order to reduce average harvesting costs by taking advantage of the economies of scale. Apart from the exclusion of non-concavities in the growth function $F(x)$, we will see that the assumption of zero fixed costs plays an important role in BWW's proposition. In fact, as LS's (1982) model helps to clarify later, this assumption is implicitly assuming that to reduce h levels is a *costless* decision. Using the notation that we defined at the beginning of this section, the BWW's result requires not only supposing that $Q=0$, but also that $R=0$.

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[36] Berck (1979) cites other papers that follow similar arguments.

[37] The cost function $C(h,x)$ is *defined* as corresponding to *y* combinations such that harvesting operations imply a least y-cost, for any given x level and any desired harvest rate h. The explicit functional form of $C(h,x)$ is motivated as a combined result of (i) a Cobb-Douglas harvesting technology and (ii) the price taking behaviour of harvesting firms.

Closely related to BWW's arguments, there is a complementary line of arguments that offers a way out to the possibility of a collapse. The basic proposition is that fishing collapses are avoidable if the harvesting cost function $C=C(h,x)$ is 'sufficiently responsive' to changes in x levels when x approaches dangerous levels such as x_m, even for cases of free access to x and non-concavities in the growth function. Clark (1971) is an example showing how *constant* average harvesting costs and constant selling prices help to obtain an extinction result. By contrast, several papers use the assumption that $C_x(x,h)<0$ in order to obtain stability for a positive steady state value of x. The classical paper by Scott (1955) belongs to this group. We can also quote the papers by Smith (1968), Levhari, Michener and Mirman (1982), Hartwick (1982) and Mirman and Spulber (1984). As an example, let us briefly explore Hartwick's (1982) model.

Hartwick's (1982) basic model structure considers: (1) an *aggregate* harvesting function $H=Zg(x)$, with $g'(x)>0$ and Z as *aggregate* fishing effort, (2) a proportional-to-profit entry equation ($dZ/dt= k\Pi$, $k>0$ and Π denoting profits) that characterizes a *free-access* fishery such that $dZ=0$ when $\Pi=0$[38], (3) a continuous logistic (strictly concave) growth function $F(x)$, (4) selling price responsiveness to H such that $p=p(H)$, $p'<0$, and (5) a constant cost w per unit of fishing effort. Using this structure, Hartwick proves the local stability of the steady state pair ($x^*>0$, $Z^*>0$) if two necessary conditions are satisfied.

The first condition is that the inverse demand function $p(H)$ does not sufficiently offset, via increases in price, the revenue effects $[p(H)H]$ that arise from the reductions in the aggregate harvesting return H as x becomes smaller. This condition requires that $|\epsilon|>1$, with $\epsilon=[dH/dp][p^*/H^*]$ denoting the demand price elasticicity. This condition implies that a decline in harvest, due to a decline in x, will result in a decline in industry revenue, thus dampening the potential inflow of

[38] Hartwick's discussion has no explicit modelling of each firm's optimization problem. The free entry equation solves for the endogenous variable Z.

new entrants attracted by a higher price p. This condition plays a stabilizing role because it reduces harvesting pressures when x falls.

The second condition refers to a sufficiently x-responsiveness of the average cost harvesting function $c=w/g(x)$. This condition requires that $\eta=[dg/dx][x^*/g(x^*)]>1$, where η can be interpreted as the elasticity of (average) boat catch with respect to stock size. The condition $\eta>1$ implies that a decline in x leads to a more than proportionate decline in boat catch. This condition also implies that a fall in x produces a more than proportionate increase in the average harvesting cost c. Hence, on its own this condition suggests that exit will be encouraged by a decline in x at current prices.

The necessity of both conditions is meant to ensure that reductions in x will behave as a stabilizing force with respect to free access harvesting incentives. The point to be highlighted is that again these 'cost increases' models resort to the assumption that it is *costless* to reduce fishing effort levels when low x harvesting performances create incentives to do so. Let us see how conclusions change when we explicitly introduce harvesting indivisibilities by the presence of a positive fixed cost K.

(2.E.3.b) Increasing returns in 'costly to reduce' fishing efforts.

Hoel (1978) offers a note that rejects the sufficiency proposition of BWW (1975). He argues that IRS in harvesting technology by no means suffices to make the resource safe from extinction; neither does he accept that constant or decreasing returns to scale in harvesting technology is a necessary condition to achieve a collapse outcome. Among the different *ad hoc* intuitive counter-examples that Hoel offers, all of them for a closed entry fishery with price taking and fully myopic (static optimizing) harvesting firms, he implicitly introduces the issue of *costly* downward adjustments in fishing effort levels.

Apart from the criticism that BWW exclude non-concavity effects from the growth function F(x), Hoel provides some counter-examples which imply aggregate harvests which always ($\forall x$) exceed the biological growth of stock x, in spite of exemplifying different individual harvesting technologies h(x,y) with IRS $\forall x$. Hence, despite the presence of IRS in individual harvesting technologies, the common pool resource is not safe from extinction. But *why* individual harvest rates are not downwardly adjusted in a faster way when $x \to 0$? Hoel *ad hoc* examples do not provide an explicit answer to this. Berck (1979) offers a complementary exposition which helps us to clarify the issue.

Modelling a free access fishery with a proportional-to-profits entry equation, subject to fully myopic harvesting, Berck considers the possibility of an x-range where $F(x) < 0$, calling the critical x^c level such that $F(x^c) = 0$ as the "minimum viable stock". Then Berck introduces a fixed cost $K > 0$ that defines a "minimum profitable" stock x^p. The presence of the fixed cost K introduces increasing returns in the choice of the harvesting rate. Berck's basic proposition is that collapse arguments need, to impose as a necessary condition, a restriction on the ratio $r(x) = [x^c/x^p]$ such that if $r(x) > 1$, then a collapse outcome will be possible. The underlying intuition is that the indivisibility introduced by $K > 0$ will tend to promote intensive harvesting, making the occurrence of fishing collapse more likely.

However, Berck's (1979) argument does not deal with the issue of why harvesting firms would not follow *cyclical* harvesting strategies, given the presence of fixed factors. That is, harvesting 'heavily' for a while and hence taking advantage of increasing returns in fishing efforts z, but reducing or even stopping $z > 0$ when the system F(x) approaches a 'dangerous' x level such as x^c; then allowing for a period of recovery of x and, finally, restarting harvesting only when a safer level of x is achieved. In fact, to justify the arrival at a collapse outcome would require to specify, in addition to Berck's necessary condition, the assumption that it is not profitable to stop harvesting even if we know that we are arriving at x^c. As with

Hoel's counter-examples to BWW's proposition, the latter condition calls for an assumption of costly downward adjustments in fishing effort levels.

The series of models of LS (1977, 1979 and 1982) offer a clearer exposition of the latter idea. Assuming a sole owner harvester, whose objective function is identical to that of a social planner, LS abstract from the issue of commonality externalities. Within a continuous time framework, their models evaluate the optimality of cyclical or 'pulse fishing' harvesting strategies, when the optimization problem considers non-convexities of the growth function and those arising from the existence of two different types of harvesting indivisibilities or fixed costs: (i) a fixed cost $Q>0$ that is required if $h>0$, but it is *avoidable* if $h=0$, and (ii) a fixed cost $R>0$ that is *triggered by* the decision to stop harvesting operations with the intention to resume them later.

The basic proposition from the series of LS's models consists in arguing for the optimality of *cyclical* harvesting when the harvesting technology requires quasi-fixed (avoidable) costs $Q>0$ along with positive, though 'not sufficiently high'[39], re-entry costs R. Given this particular combination of Q and R values, 'pulse fishing' strategies will not only be optimal from the sole-owner perspective, but they can also prevent collapse outcomes.

More precisely, the assumption that it is *costless* to reduce harvesting or fishing efforts, when increasing returns at low x offer incentives to do so, corresponds to a case with $R=0$. This is the framework within which BWW (1975) build up their proposition.

Along a similar line of arguments to BWW, by considering the case when $R=0$, LS (1982) argue for the possibility of 'convexifying' the originally non-convex choice problem (given $Q>0$ and $x^c>0$[40]), by making use of infinitely frequent

[39] We clarify this conditionality in the following paragraphs.

[40] The latter results from LS's modelling of critical depensation growth.

adjustments in the harvesting or fishing effort rate. Clark (1976, p.171) refers to this type of decision policy as a "chattering control" solution. The key issue in this proposition, valid only for continuous time settings, is the sole owner's ability to stop, and later resume, fishing efforts without any explicit entry or exit cost attached to the decision "set $z=0$; then resume $z>0$". In a case of this type, $Q>0$ will effectively reduce the initial level of investment in x; however, because Q is avoidable if we set $h=z=0$ when the fishery approaches x^c, 'quick' pulse fishing operations will help to avoid a problem of collapse or extinction.

Let us now impose $R>0$ costs to the use of chattering harvesting controls. If R becomes 'large enough' to discourage the use of *any* cyclical harvesting, the optimal harvesting strategy will then be to either harvest the resource on a sustained basis or to extinguish it in finite time (see LS, 1977 and 1982 for more details). The corollary is that, as $R>0$ increases, harvesting indivisibilities (generated by $Q>0$) tend to increase the likelihood of attaining extinction as a dominant (preferred) strategy within the sole ownership framework.

If, on the contrary, the relevant fishery setting defines an 'intermediate' level for $Q>0$ and $R>0$, a regeneration cyclical harvesting strategy can become optimal; that is, to stop harvesting to avoid fixed costs Q; then to allow stock x to increase and to recuperate; and finally, to restart harvesting when the stock has become large or safe enough.

In other words, increases in $R>0$ tend to increase the time taken on each harvesting cycle[41] (the 'cycle length') and also tend to increase the difference between the upper and lower bounds for the stock x levels[42]. By contrast, as $Q>0$ increases, *ceteris paribus*, the time spent in harvesting operations tends to be reduced, because of the more intensive harvesting that arises from the indivisibility introduced by Q.

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[41] Or, a greater R tends to reduce the 'periodicity' of each cycle.

[42] Or, a greater R tends to increase the 'amplitude' of the harvesting cycles.

In the case of *discrete time* settings it is not feasible to 'convexify' an originally non-convex optimization problem by 'infinitely rapidly' setting and changing the harvesting rate, even if $R=0$ (see Clark, 1976). Instead, for cases with $Q>0$ and $R=0$ the optimal policies correspond to *cyclical* harvesting strategies. They resemble the "regeneration/exploitation" strategies that arise within continuous time models with $Q>0$ and $R>0$. Other combinations between Q and R values, within discrete time models, imply qualitatively similar results to those already described for continuous time settings. The models of Spulber (1983), Jacquete (1974) and Reed (1974) are some examples of discrete time models, with sole ownership and $Q>0$ assumptions, that bring about results in favour of optimal pulse fishing strategies. These three models also consider random shocks within the growth function $F(x)$.

(2.F) Final remarks.

There is no doubt that the issue of long-run sustainability has played, and still does so, a prominent role within the discussion and implementation of fishing regulations. However, in policy oriented debates we find ambiguities in concept definitions and causality arguments. These ambiguities can be partially understood as the result of technical complexities that one encounters when more rigorous analyses of this issue are attempted. Multiple equilibria issues, dynamic considerations, uncertain states of nature, irreversibility of capital stocks, and incomplete property rights are some of the key issues that are combined within the sustainability debate in fisheries.

This chapter has attempted to contribute to build a bridge between rough simplifications that practical policy implementation imposes on the analysis, and abstractions from other important issues that more rigorous analyses need to make. We have tried to make headway on the precision of some key concept definitions and also on the causality arguments that underlie policy oriented discussions concerning fishing regulations.

One of the main messages is that fishing regulators and related analysts need to make as explicit as possible the welfare model that they are using as a yardstick of evaluation. The multiple dimensional feature of the sustainability debate makes the latter requirement an essential component of fishing regulatory arguments.

A corollary that emerges from this requirement is to realize that collapse concerns are only an alternative cost argument. A collapse outcome does not imply, *a priori*, a net welfare worsening result. This type of welfare proposition would make it necessary to prove not only that collapse is a possible result and that what is lost is a valuable asset, but also that the value of those capital losses overcompensates the private benefit streams that motivate the occurrence of a fishing collapse.

As usual, many important issues have been left untouched. The relevance of uncertain nature's states within marine industrial fisheries is one of them. It also remains as a challenge to advance on the explicit consideration of commonality externalities, and the corresponding hypotheses regarding harvesters' strategic interactions, in the adjustment cost effects that emerge from harvesting indivisibilities and sunk installed capacity. The combination of fish stocks' commonality and the indivisibility of harvesting technologies undoubtedly affects the incentive structures that can lead to fishing collapses.

Closely related to this challenge, it remains to advance further on the optimality evaluation of cyclical or 'pulse fishing' harvesting strategies. Empirical evidence from industrial fisheries confirms the relevance of this type of depletion strategy.

CHAPTER 3
ON THE REGULATION OF MARINE INDUSTRIAL FISHERIES: THE CASE OF CHILE

(3.A) Introduction

This chapter analyses the history of Chilean fishing regulations over the last five decades. We focus on the evolution of access restrictions and catch quotas. We analyse the fishing regulator's persistent inability to enforce annual quotas. Distributive conflicts and triggered lobbying powers play an important role in the explanation of this phenomenon. We analyse the possibility that private interest groups have partially *captured* the regulatory decision making process. An in-depth analysis, which is consistent with the latter line of thought, is developed to explain the Chilean fishing law of 1991. This was finally enacted after a protracted period (three years) of negotiations among the government, the fishing regulators, and the main lobbying groups who represented the more powerful private interest groups that were affected by the proposed regulatory changes.

For more than 50 years Chilean marine industrial fisheries were ruled by a criterion of *historical rights* in the issuing of fishing permits. This form of regulation made it possible to have some control on access to the fisheries, but it did not solve the common property issue. In fact, historical rights were combined with the cyclical use of access restrictions and direct controls on fishing efforts. Global annual catch quotas were suggested in several periods, but always without effective enforcement powers.

This latter feature can be mainly explained by the lack of political support for the enforcement of more restrictive fishing regulations. Over this period, other policy objectives (e.g., industrial development, reduction of the State's direct regulatory role, success of reprivatization reforms) had higher political priority. The relative high abundance of fish stocks surely contributed to shape these priorities. This chapter also analyses the possibility that regulatory capture by private interest groups may have affected the regulatory outcomes. Partial evidence in favour of this latter argument is discussed.

In the late 1980s, a controversy arose with respect to the prevailing regulatory framework for fisheries. Most of the initial discussions hinged on how efficacious and efficient different *regulatory instruments* were. As time went by, factors of a more institutional nature began to be given consideration. Among the latter, a key controversy concerned the constitutionality of the State's rights to limit access to fisheries and to sell *full* property rights over fish stocks.

On the issue of regulatory instruments, one of the key reforms that was proposed attempted to implement a system of individual transferable (catch) quotas (ITQ) for the most important fisheries in the country. However, a strong opposition arose from the long-established incumbent firms catching in the Northern fishing grounds. Fish stocks in this region had been heavily exploited and catch performances had been steadily falling since the mid 1980s. Therefore, Northern entrepreneurs wanted to reallocate part of their fishing efforts towards the more abundant Southern fishing grounds. Southern incumbent firms, by contrast, were more sympathetic to the use of ITQs regulations, but if and only if ITQs were initially allocated according to regional historical rights. This initial access restriction, given the expected positive pricing of ITQs, would help to reduce the competitive pressures that were arising from the Northern firms' desire to reallocate part of their fishing activities towards the South. As a result, Northern firms (which were highly concentrated) became the main lobbying power opposing the use of ITQs and other types of access restrictions to the Southern fishing area. Then a complex multi-part bargaining over the proposed regulatory changes started, stemming from the distributive disputes among the vested interests. It took more than three years and six deferrals in Congress until a new fishing law was finally enacted in September 1991.

The resulting fishing law is a *hybrid* between two earlier proposed bills. It retains free access as the general framework, subject to *transitory* entry restrictions if conditions of *biological* overfishing are agreed on. The most important industrial fishing grounds (pelagic species) are currently classified in a stage of biological overfishing. This means that these fisheries are kept under (annually renewable) closed entry regulation. Direct control mechanisms over fishing efforts virtually disappear, as for instance the previous limits on fleet's fishing capacity. More biologically oriented controls on fishing efforts (such as seasonal closures, minimum net sizes, minimum catch sizes) remain within the set of policy instruments. With respect to quota devices, the new fishing law provides for the use of global and individual quotas on catches, but without defining a set of *compulsory* triggering conditions for their use. This and other administrative procedures significantly reduce not only the importance of ITQs within the current set of regulatory instruments, but also with respect to their role in the originally proposed bills. Another novelty of the new fishing Law consists in vesting several private lobbies with partial resolutive powers in some of the most important areas of regulatory decisions.

The analysis in this chapter is the first to combine a detailed and consistent historical analysis of Chilean fishing regulations with new information on the industrial structure of the main fisheries under regulatory control, while emphasizing an "interest group" theory perspective in the analysis of private lobbying efforts to capture the regulatory outcome.

The discussion is organized as follows. Section (3.B) describes the relative size and temporal evolution, in terms of tonnage caught, of the main Chilean fishing grounds and fish species under industrial exploitation. Section (3.C) discusses the phenomenon of industrial concentration that prevails at some of the most important Chilean (pelagic) fisheries. Personal interviews with fishing experts and entrepreneurs, and our own collection and aggregation of detailed micro (at the firm level) statistical information, support the analysis in this section. Section (3.D) reviews the main policy objectives (stability and efficiency aims) that are usually resorted to in order to justify the need for fishing regulations. This discussion helps to clarify the key issues at stake in the negotiations to set up specific fishing regulations. Section (3.E) briefly reviews the history of Chilean fishing regulations. Emphasis is placed on the analysis of access restrictions and catch quotas. Section (3.F) analyses four possible and complementary explanations of the persistence of enforcement weaknesses in the regulatory agencies' attempts to implement binding annual catch quotas. The arguments analysed deal with government's objectives and policy priorities, the institutional organization of regulatory agencies' tasks, information problems that surround the implementation of catch quotas, and the possibility of regulatory capture effects. Section (3.G) analyses in depth the late 1980s regulatory controversies that were triggered by the enactment of a new Chilean fishing law. Special emphasis is put on the analysis of the distributive conflicts and the resulting lobbying pressures that surrounded, and partially captured, the negotiations on fishing regulatory schemes. Finally, section (3.H) offers some concluding remarks including a comparison with other major fishing countries' experiences in regulating common pool marine industrial fisheries.

Main abbreviations.

IFOP:	Development Fisheries Institute.
SUBPESCA:	Undersecretaryship of Fishing.
SERNAP:	National Fishing Agency.
CORFO:	National Development Agency.

(3.B) Chilean fishing grounds and main fish species.

In this section we offer an introductory description of the most important Chilean marine industrial fisheries. The objective is to describe the relative importance, in terms of tonnage caught, of the main fishing areas and fish species. We also describe the main (processing) uses of the fish caught, and the temporal changes in the relative importance of the main fishing grounds. We focus on *fish species* fisheries, given their predominant importance within the country's total catches. We do not consider fisheries related to the harvesting of algae, molluscs and crustaceans[1].

Table 3.1 shows Chilean fish species catches, measured in thousands (000) of tons, during 1993. These catches include the harvesting of 73 different classified fish species. The main fish species, in terms of tonnage caught, are shown in Tables 3.2 and 3.3. Table 3.1 shows the relative importance of industrial, artisanal, and fish farming fisheries within the country's total harvesting[2]. Industrial fisheries represent around 90 per cent of this total. At fish farming[3] and artisanal[4] fisheries the tragedy of the commons tends to be ameliorated, mainly because of lower costs of enforcing exclusive user rights versus the case of marine industrial fisheries (see Ostrom, 1990; Libecap, 1989; Eggertsson, 1990). As in the rest of this thesis, in this chapter we focus our analysis on the latter category of fisheries.

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[1] During 1993, Chilean total catches of all *fish species* accounted for 5.86 millions of tons. This includes the catches from foreign factory boats; algae accounted for 155 thousand tons; molluscs for 110 thousand tons, and crustaceans for 26 thousand tons. As an indirect measure of the relative size of Chilean catches in world terms we can mention that, during 1985-86, the average annual total catches (including fish species, crustaceans and molluscs) in the USA were equivalent to 2.87 million tons, 5.88 million tons for the aggregate catches from the main fishing countries within the EEC (Spain, Denmark, UK, France, Italy, Portugal and Germany), 1.36 million tons for Canada, and 3.62 million tons for the aggregate catches from Norway and Iceland. In all these cases, the definition of each country's total catches considers national landings in domestic ports, according to OECD statistics (*Review of Fisheries in OECD Member Countries*, OECD, 1987, Paris).

[2] This total does not consider the harvesting from *factory boats* which accounted for 60.1 thousand tons during 1993. Factory boats are usually owned by foreign fishermen and mainly operate outside Chile's exclusive fishing zone.

[3] The majority of fish farming is developed in the Austral fishing zone. In 1993 salmon farming accounted for 55.2 thousand tons and trout farming for 22.2 thousand tons.

[4] *Artisanal* fisheries usually correspond to fishing grounds harvested by small size boats. In the case of Chilean marine fisheries, *artisanal* boats usually operate no farther than five marine miles from the coast. In the case of pelagic fishing grounds, *artisanal* boats are defined as those with a cargo capacity no greater than 50 tons.

Table 3.1 also gives information on the main fishing areas within the country. Fishing experts and marine biologists agree on dividing Chilean fishing grounds into four main geographical areas, each of them distinguished by specific biological conditions and behaviour of the fish populations that they include. Northern fisheries are divided into two fishing grounds, where zone A concentrates the majority of the harvesting in the Northern region. Harvesting in zone A accounts for 35 per cent of national fish catches. In the south of the country, the Austral fishing zone is mainly specialized in fish farming, but it also includes industrial harvesting of some important demersal[5] fish species (Table 3.3). But the majority of the catches from Southern fishing grounds comes from the VIIIth region[6] which, in 1993, concentrates the higher regional harvesting, accounting for 54 per cent of national total catches. As in the case of the Northern zone A, these fishing grounds are predominant in *pelagic* species (Table 3.2), although they also generate harvesting of some valuable *demersal* fish, as is the case of hake species (Table 3.3).

Northern zone A is the Chilean fishing ground which is closest to Peruvian waters. In this area some of the main fish species are harvested by the Chilean and Peruvian fleets[7]. This zone concentrates the historically most important Chilean industrial fishing grounds, which started their industrial development in the mid 1950s. A majority percentage of the harvesting in this zone is devoted to fish meal production (Table 3.4). Most of the catches in this region corresponds to *pelagic* fish

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[5] Demersal fish species are white food fish, usually harvested by trawl net fleets, and mainly used for direct human consumption. These fish species tend to live deeper in the ocean than pelagic species.

[6] This region is nearly 500 km to the south of Santiago, and approximately 2000 km to the south of the Northern fishing grounds in zone A.

[7] For example, the Chilean Development Fisheries Institute (IFOP) estimates that in this region 60 % of the anchovy stock is shared between Chilean and Peruvian fleets. In the case of other fish species, such as sardines or South Pacific pilchard, that percentage drops to around 5% (source: interviews with IFOP's fishing experts).

species, with mackerels, anchovies and sardines as the three most important species (Table 3.2).

Pelagic (shoaling) fish species tend to be more abundant but more variable than other fish stocks, e.g., *demersal* species. They are more variable, in their availability at a given fishing area, because they have significant migratory patterns and also because their stock levels tend to be highly variable through time[8]. Pelagic species also live near the surface, in densely concentrated fish patches; hence, they have a relatively low harvesting cost (per ton of fish caught). They are fish with darker and more oily flesh than *demersal* species. Due to these features, they are not very attractive for direct human consumption and, therefore, they are mainly used for fish meal production.

Pelagic fish species are also dominant among the industrial catches from the Northern fishing zone B and from the most important fishing area in the Southern regions, that is, the fishing grounds in the VIIIth region (Table 3.2). As a consequence, fish meal production is also dominant among the industrial processing industries in this latter region. However, in this Southern region canning and frozen-fish industries also show some degree of development, accounting jointly for nearly 200 thousand tons of processed raw fish or 6.5 per cent of the total tonnage of raw fish processed in that zone (Table 3.4). Canning and frozen-fish industries are based on the processing of demersal fish species.

Demersal fish catches are mainly concentrated at the Southern fishing grounds in the VIIIth region and Austral fisheries (Table 3.3). Factory boats tend to operate moving from one fishing ground to another, but in the case of demersal species factory boats always operate in the proximity of Austral fishing grounds. Harvesting in the VIIIth region, from artisanal and industrial fishermen, accounts for nearly 55

[8] Pelagic stocks are usually short lived and faster growing in comparison to other important fish species, e.g. demersal species. As a consequence of this, they are more exposed to recruitment fluctuations. And recruits (juvenile individuals) in these fish populations tend to show high variability due to environmental shocks.

per cent of the national harvesting of the main demersal species, whereas factory boats' harvesting accounts for nearly 25 per cent of this total. The harvesting at international waters fisheries is mainly carried out by foreign fishing fleets.

Table 3.5 shows the temporal evolution of total *pelagic* industrial catches from the two most important fishing areas in Chile: the Northern region A and the Southern VIIIth region. It also includes information on Peruvian total pelagic harvesting during the 1970s and 1980s[9]. This latter series allows us to observe the harvesting consequences from the collapse of the Peruvian anchovy fishery that occurred between 1972-73 (see section 4.C.2).

Pelagic fish catches in the Northern zone A show an increasing trend since the mid 1970s, a period in which a widespread process (across productive sectors) of reprivatization took place in the Chilean economy[10]. The increasing pelagic catches in the Northern zone A achieved a peak level in 1986. This evolution was parallel to an increasing size of the industrial fishing fleet operating in this zone. The number of purse-seine industrial boats[11] increased from 116 in 1978 to 182 in 1986. The cargo capacity of the fishing fleet increased from 19700 m^3 in 1978 to 45900 m^3 in 1986 (IFOP's statistics)[12]. This increasing scale of operation occurred during a period of a *de facto* open access to these fishing grounds.

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[9] Recall that part of the Peruvian pelagic catches come from fish populations that are shared with Chilean harvesting operations in the Northern zone A.

[10] The reprivatization of the Chilean fishing sector was consolidated in 1978.

[11] This is the predominant type of fishing boat that operates in modern industrial pelagic fisheries.

[12] At 1993, the number of purse-seine fishing boats was 157 while the fleet's cargo capacity was equivalent to 46600 m^3 (IFOP's statistics).

Table 3.1
Chilean Fish Catches, 1993
(all fish species; tons, 000)

	Northern Fisheries		Southern Fisheries		Others	Total Country
	A	B	VIII	Austral		
Total	2015.1	266.8	3126.2	96.9	285.1	5790.1
Industrial catches	1914.7	216.8	2863.6	11.3	255.4	5261.8
Artisanal catches	100.4	50.0	262.6	9.5	28.3	450.8
Fish farming	-	-	-	76.1	1.4	77.5

Chile is divided into 12 different administrative regions.
A : considers regions I and II; B : considers regions III and IV
VIII: 8[th] region; Austral: Regions X+XI+XII.

Table 3.2
Chilean industrial catches, 1993
main fish species
(tons, 000)

Fish species	Northern fisheries		Southern fisheries (VIII[th] region)	Other Regions	Total Country
	A	B			
Anchovies (P)	1094.3	67.0	69.3	64.9	1295.5
Pacific Mackerel(P)	93.7	0.4	0.8	-	94.9
Horse Mackerel (P)	374.8	93.0	2569.1	164.9	3201.8
Chilean hake	-	0.1	42.2	9.3	51.6
Tailed hake**	-	-	70.4	0.5	70.9
Sardine* (P)	350.0	55.3	29.7	6.8	441.8
Pacific Herring (P)	-	-	79.6	8.0	87.6
Others	1.9	1.0	2.5	12.3	17.7
Total fish species	1914.7	216.8	2863.6	266.7	5261.8
(%)	(36.4)	(4.1)	(54.4)	(5.1)	(100)

A : includes regions I and II; B : includes regions III and IV.
P : denotes pelagic fish species.
* : also called South Pacific Pilchard.
**: demersal species that shows seasonal pelagic behaviour.
Source for Tables 3.1 and 3.2: Annual Fishing Statistical Report, 1993, SERNAP.

As a result of these patterns, since the 1960s and until the late 1980s the Northern pelagic fisheries were clearly the most important industrial fisheries in Chile. However, since the early 1990s this region has lost its predominant position as the leading fishing ground. The significant and persistent harvesting at zone A has reduced the population levels of some of the main fish species which are caught in zone A.

The graphs in appendix 3.1 show the time evolution of fish stocks and catch levels of two of the main pelagic fish species (sardines and horse mackerel) that have sustained the fishing activities in zone A. Official (IFOP's) fish stock estimations and catch statistics are originally measured in tons. Fish stock estimations add individuals' weight across different age cohorts. We have calculated indexes with basis 1985 = 100 for fish stocks and catch (tonnage) series.

In the case of sardines we clearly see the beginning of a decreasing trend in fish stock levels at zone A since the early 1980s. Then a clear pattern of decreasing catches follows, with a time lag of 4-5 years. In fact, sardine annual catches in zone A reached a peak level of 2.6 million tons in 1985, and then started a decreasing pattern until reaching a level of 630 thousand tons in 1992.

In the case of horse mackerel annual series, we observe a less trended but more cyclical pattern versus the case of sardines. On average, horse mackerel stock levels in zone A tend to increase during the first half of the 1980s, but since 1985 they experienced a clear fall in their levels. The harvesting series look positively correlated to the stock levels, and for the early 1990s we can observe a lower average annual catch versus the average between 1981-85.

Table 3.3
Catches of main demersal fish species
Main fishing grounds, 1993
(tons, 000)

Species	Southern Fisheries		Factory boats' harvesting	International waters fisheries	Total country
	VIII Region	Austral			
Tooth fish	1.1	2.0	4.4	11.9	22.0
Chilean hake	46.3	0.5	-	-	64.3
Austral pollack *	-	-	27.6	-	27.6
Antarctic whiting	-	10.5	9.7	-	20.1
Tailed hake	70.6	-	11.4	-	82.6
Total	118.0	13 0	53.1	11.9	216.6

Notes:
Total country catches consider industrial, artisanal and international waters harvesting. It includes catches from other minor fishing grounds in addition to those considered in this Table.
Austral fisheries: considers catches in regions X, XI and XII.
*: also known as blue whiting
Source: Annual Fishing Statistical Report, 1993, SERNAP.

Table 3.4
Main processing fishing industries
Tons (000) of processed raw fish, 1993

	Northern Fisheries Zone A	Southern Fisheries VIII[th] Region
Canned fish	23.2	127.8
Fish meal	1932.1	2764.3
Frozen fish	5.3	69.2
Others	4.3	1.3
Total regional use of raw fish	1964.9	2962.6

Note: Supply sources need not belong to the own region.
Source: Annual Fishing Statistical Report, 1993, SERNAP

Table 3.5 shows an aggregate summary of the decreasing pattern in pelagic species catches in the Northern zone A since the late 1980s. The average annual catch in this zone has decreased more than 1 million tons when we compare the average performance between 1985-89 with the annual catches between 1990-92. This is a result of the booming harvesting pattern that started around 1977-78. Since 1989 the pelagic fisheries in zone A have been declared, by the fishing regulatory agency, in a stage of *biological* overexploitation (see below).

In contrast with the evolution of the Northern pelagic fisheries, Table 3.5 shows increasing annual catches from the pelagic fisheries located in the Southern VIIIth region. In terms of tonnage caught, fishing grounds in this region were clearly less important than Northern ones during the 1970s. However, the beginning of a *laissez faire* regulatory policy since 1977-78, that permitted an open access regime for all pelagic fisheries, helped to promote increasing fishing efforts and harvesting levels in these Southern fisheries.

In fact, since 1981-82 a process of significant entry to these fisheries started[13], implying the increasing harvesting levels which are shown in Table 3.5. During the early 1990s, annual pelagic species catches at the VIIIth region have been clearly above Northern catches: in 1992 and 1993 Southern harvesting has been around 3 million tons, while in Northern zone A annual catches have been around 2 million tons. Nonetheless, since the end of 1989 the pelagic fisheries in the VIIIth region have also been declared in a stage of biological overexploitation by the fishing regulatory agency. In the following sections we will see that this stage had closed entry and a *freezing* of fleet cargo capacity.

[13] IFOP's 1993 annual report on Chilean pelagic fisheries describes an increase of 200 %, between 1982 and 1993, in the number of purse seine boats that operate as part of the industrial fleet in the Southern VIIIth region. In the same period, the aggregate cargo capacity of the industrial fishing fleet increased 9 times with respect to its 1982 level. At 1993, 133 boats were operating in this region, with an aggregate cargo capacity of 77000 m^3.

(3.C) Industrial structure in the main Chilean marine fisheries.

In this section we present information on the phenomena of industrial concentration and vertical integration that we encounter in some of the main Chilean marine industrial fisheries. Our current interest in the concentration issue stems from its impact as a source of significant private lobbying powers, and the influence of the latter in terms of *'capturing'* the regulatory agencies' decisions. The following sections explore these ideas.

Reliable and detailed statistical information on the industrial composition of Chilean fisheries is very scarce indeed. We have been unable to find serious studies on the industrial structure of these fisheries[14]. However, based on our own calculations that have used different disaggregated sources (most of them at the firm's level), we have been able to collect and aggregate information on production series that support the existence of a partial degree of industrial concentration in the main Chilean marine fisheries.

For example, in the Southern VIIIth region the biggest 10 fish meal processing firms[15] produced nearly 80 per cent of the regional exports of this product during 1992 (Table 3.6). Export data are a very close statistics of production data, as the Chilean fish meal industry exports no less than 95% of the country's total production. This evidence in favour of industrial concentration in the production of fish meal is also an evidence of the presence of concentration in harvesting operations. Through our contacts with fishing experts[16], we have (verbally) verified that around 60 per cent of processing plants' raw material (raw fish) is supplied by boats which are *directly owned* by the processing firms, while the remaining 40 per cent is obtained from independent suppliers.

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[14] Some introductory analyses can be found in Duhart and Weistein (1988), and SUBPESCA-CORFO's (1989) *mimeo* report.

[15] Most of the industrial catches in this region are used in fish meal production (Table 3.4).

[16] We thank H.Lampe (IFOP) on this point.

Table 3.5
Pelagic fish industrial catches (tons, 000)
Main fishing grounds: Chile and Peru

Years	Chile			Peru (5)
	North* (zone A) (a)	South ($VIII^{th}$ region) (b)	Total (a+b)	
1970	813.3	87.6	900.9	12481.1
1971	1008.8	204.5	1213.4	10505.2
1972	358.5	150.1	508.6	4673.1
1973	269.0	159.5	428.5	2290.0 (3)
1974	661.6	193.6	855.2	4120.0
1975	533.8	104.6	638.4	3409.2
1976	960.2	103.5	1063.7	4357.8
1977	926.0	124.3	1050.3	2491.4
1978	1416.3	194.8	1611.1	3430.3
1979	1846.1	307.3	2153.3	3639.4
1980	2078.0	332.6	2410.7	2697.1
1981	2159.3	543.1	2702.5	2700.9
1982	2540.9	708.3	3249.3	3497.0
1983	2708.7	582.5	3291.2	1537.0
1984	3009.5	510.7	3520.2	3288.4 (4)
1985 (1)	3155.2	867.5	4022.7	4110.3
1986 (2)	3604.6	1098.0	4702.6	5529.5
1987	2345.2	1635.4	3980.7	4347.9
1988	2490.6	1847.5	4338.0	6598.4
1989	3039.3	2246.7	5286.0	6817.0
1990	1772.6	2049.6	3822.2	
1991	1732.7	2675.6	4408.3	
1992	2066.0	3046.0	5112.0	
Average 85-89	2927.0	1539.0	4466.0	5480.6
Average 90-92	1857.1	2590.4	4447.5	

(1) Seasonal closures begin in this year.
(2) Freezing on fleet's storage-capacity, in the North and $VIII^{th}$ region, starts this year.
(3) May 7^{th}, 1973: Beginning of State-owned firm "Pesca Peru".
(4) Peruvian private fishing sector is "reactivated".
(5) Peruvian total pelagic catches (purse seine fleet). Source: Sueiro (1991).
* Zone A: regions I + II.
Source: Records from Chilean Development Fisheries Institute (IFOP) and private sector firms.

We do not have precise information on the temporal evolution that preceded the current situation of industrial concentration at the Southern pelagic fisheries. However, the regional harvesting trends that are shown in Table 3.5 lead us to conjecture that the Southern concentration phenomenon is probably a result of the recent expansion period that has occurred in these fishing grounds[17].

For the case of the Northern pelagic fishery (zone A) we have been able to collect some additional detailed information. Hence we concentrate our next comments on this marine industrial fishery. The process of *private* industrial concentration in this fishery started in the mid 1970s. Hence it is an older phenomenon than in the Southern fisheries. Also the current level of industrial concentration in this fishery is higher than the one currently prevailing in the Southern pelagic fishery.

Since its origins as an industrial fishery (1954-57), Northern fishing grounds have experienced two periods subject to industrial concentration. The first one, between 1967 and 1973, was the result of a *de facto* public takeover of the ownership and managerial control of the most important firms in the industry. This result, close to a case of public monopoly, was a policy response to a widespread problem of financial bankruptcy risks that had affected private firms working in the industry[18].

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[17] Personal interviews with Chilean fishing experts (H.Lampe, IFOP) have informally ratified this conjecture. IFOP's *1993 Annual Report* confirms that until 1982 the size of the Southern fleet operating in the VIIIth region was quite stable, and that only since then an important growth period started.

[18] At the peak (1966) of the fishing boom of the 1960s, which occurred in Northern zone A, there were 25 privately owned industrial fishing firms. After the bankruptcy crisis of the late 1960s, from the 10 surviving fishing firms 7 of them had, in 1970, state ownership shares that ranged between 40 to 100 per cent. These shares increased to almost full state ownership during 1971-73, period in which a socialist (Allende's) government attempted to implement profound changes in the ownership structure of the country (CORFO Reports, Industry Department, 1970).

Table 3.6
Chilean Southern pelagic fishery (VIII[th] region)
Share of biggest processing firms
in regional fishmeal exports

	1991	1992
5 biggest firms (%)	40.9	45.0
10 biggest firms (%)	67.7	76.2
15 biggest firms (%)	87.6	91.9

Source: Chilean Development Fisheries Institute (IFOP), based on Custom's information.

Such a situation was partially the result of a combination of[19] (a) 5 to 6 years of rapid expansion in the industry's total catches, as an open access situation and attractive profit margins encouraged the increasing entry of newcomer harvesters; (b) financing of this expansion with subsidized *cheap* public credit, aimed at promoting industrial development, that provoked risky increases in the private firms' debt-equity ratios; and (c) the occurrence in 1965 of a strong "El Niño" marine phenomenon, that significantly reduced the harvesting performances within this industry[20]. A similar public monopoly fishing policy took place in the Peruvian anchovy fishery between 1974-84 (see Table 4.1). Again this was the result of the fishing authority's reaction to an economic collapse problem in this fishery (the 1972-73 collapse).

In the Chilean case, the public ownership policy was fully reversed between 1974-78, a period in which a widespread process of reprivatization took place in the Chilean economy. This policy was part of a profound economic transformation process that started after the military coup of 1973. As a result of the 1974-78 public

[19] More details in Amenabar (1972) and Alvarez (1993).

[20] As a reference, during the 1960s this fishery was mostly dependent on the harvesting of anchovies. In 1954 the annual catches of this species were 1100 tons in the Northern region. At the peak of the 1960s-expansion period of this industry (year 1966) these annual catches had increased to 1 million tons. In that same year, the installed fish meal productive capacity was able to process 5 million tons/year, that is, five times the current level of the annual catches (CORFO Reports, 1970).

auctioning of all the State's rights in the most important fishing firms, an increasing pattern of *private* industrial concentration started to emerge in the most important industrial fishery at that time, that is, the Northern pelagic fishery.

Appendix 3.4.A shows the Northern industry's total harvests between 1974 and 1992. Each measure of catches, in thousands (000) of tons, has its corresponding index value with 1980 as the base year (100). Appendices 3.2.A and 3.2.B plot part of this data. We provide information on the harvesting of three sets of firms.

The set denoted by *Other firms* covers a group of relatively small firms, which in 1989 represented approximately 40 firms, that in the late 1980s and early 1990s accounted for slightly more than 20 per cent of the industry's total catches[21]. Most of these firms only perform harvesting operations[22], selling their (raw fish) catches to fish meal processing plants. These plants are owned by firms that are vertically integrated to harvesting fleet's operations. The group of small firms supplies its production to these vertically integrated firms, in several cases under exclusive ties or long run contracting mechanisms.

Coloso is a multi-boat and multi-plant vertically integrated firm that has historically represented around 20 per cent of the industry's total production[23]. During most of the period 1974-92, its ownership structure has been controlled by family tied equity rights.

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[21] In 1993 this subgroup was reduced to 24 independent harvesting firms. In the original IFOP's statistics, each industrial boat is correlated to the name of the owner company. However, for small firms that own 1,2 or 3 boats, the original source only uses the label "private owner" for each boat's ownership. Hence we cannot distinguish between harvesting firms that own only 1 boat versus 2-3 boats. We have followed the convention to consider each boat entry denoted by the label "private owner" as an independent single boat firm. In 1988 there were 35 entries of this type. In 1993 there were 21.

[22] In 1988 only 6 firms within the group of *Other firms* owned at the least one fish meal processing plant (SERNAP).

[23] In 1993 Coloso owned 28 industrial harvesting boats that operated within Northern zone A. In the same year, the Angelini group had direct equity control over 87 harvesting boats in this region. The regional industrial fleet in 1993 included 157 harvesting boats (IFOP's unpublished statistics).

The *Angelini group* is a conglomerate of several firms (Appendix 3.4.B), also with vertically integrated operations of the processing and harvesting stages, all of which are equity and strategically controlled by a single owner. This conglomerate was consolidated during the 1974-78 reprivatization period. Since the mid 1980s, the *Angelini group* has represented around 55-65 per cent of the regional annual industrial catches.

Despite the equity connections across firms belonging to the *Angelini group*, each firm has its own managerial staff with independent decision making powers in several important areas (mainly operational ones). Similarly, there exists a widely accepted perception, within the insiders to this industry[24], that firms belonging to the *Angelini group* have predominantly behaved as rival competitors in terms of harvesting strategies[25]. However, and based on similar sources of information, since 1991 there seems to be greater coordination between these different firms' fleet harvesting operations and processing plants' production decisions[26].

Appendix 3.2.B plots the temporal pattern of each subgroup's share in the regional annual catches. This graph also plots the index (1980=100) of the industry's total catches in each year. Its level is measured in the left vertical axis. The shares

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[24] Information obtained in our previously mentioned interviews during 1993-94.

[25] We could propose that rival harvesting strategies across firms in the *Angelini group* are due to two main factors: (1) an apparently static maximizing behaviour, explained in part by the commonality issue and partly by relatively high costs in enforcing each firm's exclusive harvesting, that could lead to the main objective of maximizing the current level of the conglomerate's catches (bearing in mind the price taking behaviour of this industry); and (2) a hidden action incentive problem for the boat's owner (principal), consisting in monitoring and enforcing costs that arise from the boat owner's aim to maximize catch output, given a conflict of interest with the imperfectly observable fishing efforts from the boat crew's members. The principal's optimal incentive mechanism in this situation could correspond to a rival harvesting contest across the firms belonging to the *Angelini group*. The alleged 1991 change towards more coordinated (inter-firms) harvesting operations could be explained as the result of increasing harvesting costs within this fishery, given the case of biological overfishing.

[26] Greater coordination implies more centralized (coordinated) planning with respect to the geographical reallocation and use intensities of the different firms' harvesting fleets, as well as with respect to the least marginal cost of supplying the different firms' processing plants located in different geographical areas.

in the industry's total catch are measured in the right vertical axis. We can observe a negative correlation between *Angelini group*'s share and the smaller (*Others*) firms' share in total catches[27]. The relative share of the subgroup *Others* is clearly more volatile than *Coloso*'s share.

Appendix 3.3 shows the time evolution of the catch performances from the main individual harvesting firms. *Coloso* and the firm *Guanaye* are the biggest individual firms, but *Guanaye* has been part of the *Angelini group* since 1985. The next two biggest firms under the *Angelini group*'s control are *Eperva* and *Indo*. Appendix 3.4.B shows detailed information on the remaining smaller harvesting firms which are also part of the *Angelini group*. With the exception of the smaller firms *Chilemar*, *Tocopilla* and *Punta Angamos,* the remaining four firms under the control of the *Angelini group* show full vertical integration between processing and harvesting operations. The former three smaller firms supply raw fish catches to the processing operations of the other four vertically integrated firms.

Appendix 3.3 shows positively correlated catch performances among competing harvesting firms. This positive correlation is basically explained by an homogeneous *ex post* search performance, for fish stocks' locations, across different harvesting firms. It is true that bigger firms can detect fish patches more quickly, but once an important fish patch is located by one of these firms, this information quickly becomes common knowledge (in less than 24 hours).

This phenomenon is not only valid for different boats belonging to the same fishing firm, but also for boats that belong to rival firms. The key point is that private information over fish patches' locations can not be kept *private* for too long. Given the size of the marine area under depletion, the boats' engine power, and the relatively big size and high density of pelagic fish patches, the time lag in the searching success does not seem to significantly reduce the catch performances

[27] The recovery of Angelini group's share in 1985 is due to its takeover of a big harvesting firm (*Guanaye*), until that year an independent rival firm accounted for by the subgroup *Others*.

attained by the latecomers (smaller firms) to the fish patches. Hence, changes in the regional abundance of fish stocks tend to affect different firms' harvesting productivity in a similar way, all the more so when the harvesting firms have similar operational sizes.

The combination of a clear positive correlation across different firms' current harvesting performances, and the presence of a small number of firms that accounts for a significant proportion of this fishery's annual harvesting, lead us to anticipate the presence in this industry of strong private lobbying efforts aimed at opposing regulations based on binding annual catch quotas which could negatively affect the harvesting performances of incumbent firms. Related to this intuition, let us consider a final comment on the relative *economic size* of the Angelini group.

According to a recent study (Paredes and Sanchez, 1994), in 1992 the Angelini group was the *biggest* economic conglomerate in Chile. This conglomerate has diversified equity rights in several firms which operate within the fishing industry, the forestry sector, the energy sector, the insurance services industry, the retailing sector and also other minor industrial subsectors. By combining the operational (accounting) sales of all these different firms during 1992, the authors obtained a total sales level of 2,125.7 million US current dollars. As an indirect statistics of the relative economic size of this private conglomerate, we can mention that in 1992 Chilean total exports accounted for 10,125.5 million US dollars. Hence, this economic conglomerate's total operational sales were equivalent to 20 per cent of the national annual exports. National exports in that year accounted for nearly 28 per cent of the Chilean gross domestic product, GDP[28] (Central Bank statistics).

Therefore, the economic and political importance of the *Angelini group* within the Chilean economy is clear. Its importance goes well beyond the fishing industry.

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[28] The export value is a better comparative yardstick for an indirect measure of the Angelini group's relative economic size, versus the use of the GDP value, given that the latter variable measures value added instead of gross sale levels.

In the following sections we will see how this conglomerate's economic power exerted influence on important regulatory changes that recently affected Chilean fishing industries. Before this, let us consider a brief review of the main policy objectives that usually justify the use of fishing regulations. This will help us to have a clearer idea of the key issues at stake.

(3.D) Regulatory aims.

In this section we describe the main arguments which are used to justify fishing regulations. We review the meanings attached to *stability* and *efficiency* objectives that invariably permeate the discussions related to fishing regulations.

Regulatory tasks usually involve multi-objectives problems. In marine fisheries we can find transboundary resource problems[29], calling for intercountry negotiations; we can also find either explicit distributive issues at stake, explicit environmental considerations, problems referring to location-specific fishing developments, or arguments in the line of *industrial policy* aims, and so on.

However, it is clear that discussions concerning the regulation of marine fisheries tend to concentrate on two main issues: (1) *instability* and the *long-run sustainability* of the biological systems involved, and (2) *inefficient* resource allocations, essentially defined by the problem of inefficient rent dissipation that arises from the common property of fish stocks. The instability problem normally implies *overfishing* definitions based on *biological* criteria. Discussions on the *inefficiency* issue concentrate on the set of marginal *incentives* that dictate the harvesting decisions, leaving out explicit considerations of instability and multiple equilibria. Both issues imply different definitions of regulatory objectives and policy priorities when thinking of an *overfishing* problem.

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[29] In the Chilean case, the most important fishery in this situation is the Northern anchovy stock which, according to IFOP's estimates, is shared between Peru and Chile in the order of 60 per cent of the total stock, whereas other Northern fish species show shared populations in much lower percentages (around 5 per cent in the case of the sardine stock).

(3.D.1) Instability issues.

Instability arguments tend to involve two different issues: the problem of economic *collapse* and/or biological extinction, and the intent to reduce the costs of facing a high degree of fluctuation in catch performances.

(3.D.1.a) The collapse problem.[30]

This regulatory concern is aimed at ensuring the economic survival of the affected fishing industry or, in other words, the economic sustainability of the biological system under exploitation. Using different arguments, it proposes that it is too costly, in a welfare sense, to allow the economic collapse of that system, either due to explicit environmental or biological consequences or due to technological irreversibilities in the economic penalties imposed on geographically non-substitutable fishing activities. The key issue in the sustainability argument is the proposition that a *profitable* substitution between natural (fish) and artificial (man-made) capital stocks will not take place and that the high specificity of the remaining capital stocks will impede a profitable substitution and factor movements to other production processes, hence dooming that geographical location to languish through prolonged inactivity.

The collapse concern is based on the proposition that (especially pelagic) industrial fisheries face a critical level of harvesting beyond which the growth dynamics of the fish stock enters a zone of high instability, possibly leading to its economic collapse (see chapter 2). The discussions concerning the collapse argument concentrate on the conditions needed to enter this zone of growth instability and also on the degree of *controllability* of these conditions. *Controllability* means not only the knowledge we have about these conditions, but also the ability that the fishing regulatory authorities have to manipulate or anticipate them. We certainly require more studies on these issues. The information available, however, shows that the risk of collapse is real (chapter 2). Therefore, any fishing regulatory framework should consider it.

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[30] For a more detailed discussion, see chapter 2.

(3.D.1.b) The issue of undesired catch fluctuations.

There is a second interpretation of the instability issue which is less clearly expressed, even though it is also considered in regulatory discussions. This interpretation concerns undesired fluctuations in the industry's catch performances. This corresponds to a classical argument on the costs of facing *cyclical* and/or *uncertain* levels of production and income flows.

From the viewpoint of the fishing regulatory authority, the justification for this aim arises essentially from the *adjustment* costs generated, if and when it is necessary to accommodate the industry's production to different levels of operation. Therefore, the regulatory case is justified more on the basis of the costs of facing *variability* or *cycles* in production levels, rather than on risk aversion arguments or costs of facing *uncertain* income flows.

Based on the available empirical evidence on fishing regulation priorities (for instance, Scott, 1979; Charles, 1988; Cushing, 1988; Gulland, 1988; Townsend, 1990) it seems clear, however, that this dimension of the instability concern is less important, by comparison to the collapse issue, as an argument to justify regulation of fisheries. Despite this, much more work remains to be done to define *both* readings of the instability issue in a more precise manner, and also to pinpoint the welfare effects ascribable to them.

(3.D.2) The inefficiency issue.

The key issue here is the incentive problem that is generated by the common (or incomplete private) property of fish stocks. Under this property structure, even if we have closed entry to the industry, multiple harvesting firms will have incentives to equate their variable inputs' average product (rather than their marginal product) to the inputs' marginal costs. This proposition assumes that it is too costly, relative to the expected benefits, to sign and to enforce voluntary and cooperative Coasian contracts among the harvesting firms in order to *coordinate* their harvesting decisions. These transaction costs can be thought of as a consequence of *information* costs caused by costly monitoring of rivals' actions and *incomplete* information about Nature's states.

If the previous conditions prevail, none of the individual fishermen can claim or enforce exclusive rights over the use of fish stocks and hence everyone has incentives for harvesting the fish stocks until their (Ricardian) rents are completely exhausted. This will imply an inefficient dissipation of the producers' surplus. This inefficient rent dissipation is what economists call the *overfishing* outcome. Under this economic reading of the problem, the regulatory aim consists in avoiding the inefficient waste of the natural resource's Ricardian rents.

A standard way of defining the efficiency yardstick, so as to compare it with the harvesting outcome deriving from common property, consists in assuming a social planner (with the same informational constraints as those faced by private firms) who is interested in maximizing the discounted expected present value of the Ricardian rents generating from the harvesting of the fish stock during a given time horizon. These rents correspond to the difference between the harvest value and the costs of production. These costs, of course, include the operational costs of the fishing fleet as well as the alternative costs of the capital (human, physical and financial) inputs used in that production. The harvesting time path that solves this planner optimization problem is what economists call the intertemporal *efficient* harvesting outcome[31].

Let us briefly discuss how this definition of efficient harvesting relates to a regulatory criterion which has been traditionally used in fishing management: the Maximum Sustainable Yield (MSY) criterion.

[31] By definition, this optimization yardstick considers price vectors and discount factors that correspond to shadow (social) values.

On the MSY criterion for regulation.

One of the pioneers in the field of fisheries science defined the MSY criterion in 1931:

> " ...it was desirable to keep the fish stock X at such a level, or to bring X to such a level, that the maximum value of commercially utilizable fish can be drawn from it annually without causing a progressive diminution of X". (Russell, 1931).

In simpler words this means "try to catch as much fish as you can in a *sustainable* way"[32]. This concept is still frequently mentioned, and widely popular among marine biologists, as a guiding criterion for fishing management. However, this definition clearly overlooks that the *maximum* value of total production is not always the *optimal* one, once account is taken of costs and discount rates.

It is interesting to note that the concept of MSY has also been quite popular in the discussions among foresters on the optimal rotation period for a forest. Samuelson (1976) offers a remarkable discussion regarding this point, quoting references to this concept as early as 1788[33], where it is recommended that "the cut to be regulated by how much the average tree age is above or below the optimal age that maximizes steady state lumber yield per acre" (Samuelson, 1976, p. 489).

If we assume that the MSY is defined in value terms (not as a physical quantity), our welfare maximizing planner's criterion can differ from it basically due to four reasons[34]:

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[32] Assuming price taking behaviour by harvesting firms.

[33] Samuelson sets out the right solution given by M.Faustmann in 1849 but also quotes several inaccurate solutions given by great economists, among them von Thunen (1826), Fisher (1930), Hotelling (1925) and Boulding (1935).

[34] We will not give proofs for these arguments, because most of them are well reviewed in the literature. See, for example, Munro (1982), Munro and Scott (1985), Neher's introduction to Part III of Scott (1985), Clark, Munro and Charles (1985) and Spulber's survey in Mirman and Spulber (1982) for proofs and further references.

(i) Even within a steady state analytical setting[35] the maximum catch (with given prices) will not be optimal if total harvesting costs are *somehow* correlated with the fish stock size at $x=x_{MSY}$.[36] More formally, let $C=C(h,x)$ be the total harvesting cost function, where h and x are the current harvesting and fish stock levels. A necessary condition for MSY to be optimal is that $\partial C/\partial x=0$ at x_{MSY}; that is, when total costs C are independent of the stock level at x_{MSY}. If $\partial C/\partial x \neq 0$, then the MSY is not optimal. For example, if total harvesting costs are negatively correlated with x, that is, it is more costly to harvest when the stock is smaller, the optimal stock is higher than that at MSY, reflecting that a higher level of x is desired in order to decrease total harvesting costs.

The reason is that under the MSY criterion the desired equilibrium corresponds to a stock level such that the marginal change in sustainable harvesting yield, deriving from a marginal change in the stock level x, is zero[37]. To obtain an equivalence between the MSY criterion and efficiency, total harvesting costs would have to be independent of x. If $\partial C/\partial x<0$, x_{MSY} would imply inefficient overexploitation. This is the point made by Gordon (1954) and Scott (1955) and is related to what is called the "marginal stock effect" (decreasing profits due to increasing harvesting costs at lower stock levels).[38]

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[35] In the sense of concentrating the analysis only on comparisons of steady state equilibrium points, and without making explicit reference to positive time discounting.

[36] x_{MSY} is defined as the stock level at which a strictly concave instantaneous natural growth function $F(x)=dx/dt$ achieves a maximum level ($F'(x)=0$) and thereby it allows a maximum *sustainable* level of catches.

[37] This situation corresponds to the unique maximum point that is located on a strictly concave instantaneous growth function $F(x)=dx/dt$, with $F'(x)<0$ after x_{MSY}. For example, a logistic growth function.

[38] In terms of our welfare model in chapter 2, the optimality of the MSY criterion requires imposing two restrictions upon the solution rule for the problem of optimal resource depletion (see equation (9)). First, that the marginal stock effect is zero or $\partial\pi/\partial x^*=0$. Second, that the discount rate δ is also zero. Only under these circumstances the optimal rule of resource depletion is equivalent to

Let us note that this argument is valid for fisheries where the species have strong *schooling* behaviour (high densities of individuals of similar size), as is the case of *pelagic* fisheries, where it is possible that, at lower stock levels, average harvesting costs decrease due to the higher density of the fish stock[39].

If we now assume that the MSY criterion is defined as a *net* value yield (net of operational and capital costs), our planner's efficiency criterion may still differ from it basically for three other reasons:

(ii) Even if we concentrate the evaluation of optimality on *long-run equilibrium* levels (as does the concept of MSY), but allow for the incorporation of a rate of social time preferences, the optimality of the MSY catch prescription requires that the rate of time preferences be zero. If this rate is positive, the MSY will imply (social) underexploitation of the natural resource (see references in footnote 34).

(iii) If we now introduce explicit *dynamic* considerations into the analysis, in the sense of time lags or costly rigidities in the adjustment paths of fish and capital stocks[40], the MSY criterion says nothing about the optimal paths approaching the steady state optimum as this criterion is defined in a comparative statics sense.

(iv) Finally, the introduction of fish stock uncertainty adds new problems to the use of the MSY criterion, given the impact on the time discount rates and the valuation of capital stocks. This uncertainty can imply trade offs between the

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the MSY prescription; that is, to harvest the resource until $F'(x)=0$, with $F(x)=dx/dt$ representing the instantaneous growth rate.

[39] In fact, this is a dangerous complexity in pelagic fisheries, because although the fish stock can have entered a zone of depensatory (negative) growth, the catch performances do not necessarily fall, given the high density of its population.

[40] These rigidities or time lagged responses can be modelled, for example, with the inclusion of multicohort (different age groups) models for the fish stock dynamics, or via the introduction of *sunk* costs in the harvesting technology.

expected rents and risks involved. The optimal answer to that may be quite different from the MSY prescription.

Similar criticisms could be raised against other biological criteria of fishing management which, in one way or another, are based on this notion of a maximum utilization of the natural resource. For example, the "maximum yield per recruit", the "status quo catch" (the estimated catch with constant fishing mortality) proposed by Pope (1982), and the constant instantaneous coefficient of fishing mortality ($M_{0.1}$)[41] (more details in Gulland, 1988, chapters 1,5 and 6).

(3.E) Review of the legal background to the industrial fishing sector.[42]

Among the regulatory decisions concerning fishing industries, a key set of problems is related to the definition, control and enforcement of access schemes and property (user) rights over the natural resource. In this section we briefly explore the Chilean experience on these issues.

The first Chilean Code of Civil Laws (1855) defined *fishing rights* for those who first initiated the resource depletion. These rights were defined as "rights of occupation". Additional (access) restrictions were considered in terms of the fishermen's nationality and the territorial area under exploitation. The first specific Fishing Laws (1929 and 1931) retained, in essence, this basic doctrine of *historical rights*.

In 1956 *permits* for fishing operations began to be required. Initially, this was a pure access regulation. However, since the early 1960s (Law Decrees No. 597, 1960, and No. 524, 1964) the fishing authorities intended to link the issuing of new

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[41] In this criterion M corresponds to the ratio between the catch and the average fish stock (with both variables measured in numbers of individuals). Its value $M_{0.1}$ corresponds, for a given model of biological growth, to "a level of fishing effort less than that which produces the MSY, in order to prevent an overshoot due to errors in the system of stock assessment (VPA or Virtual Population Analysis)". See Cushing (1988, page 263).

[42] For some comments on the history of Chilean fishing laws, see Montt (1985).

permits (in terms of firms and vessels) to the compliance with objectives of maximum global permissible (annual) catches (MPCs). When global effective catches approached the maximum permissible level, the intention of the regulator was to close the entry to that fishery.

However, during all this period these permissible catches were more of a signal to the private sector, rather than an effectively *enforceable* quota policy[43]. In fact, during the 1960s the dominant policy aims were promoting the industrial development of marine fisheries and improving the information on different aspects of the fish populations. As a result of these priorities, the effective regulatory instrument during this period was entry restriction via fishing permit applications. This regulatory scheme prevailed until the mid 1970s.

In the mid 1970s there was a wave of criticism against the doctrine of *historical rights*, which still dominated the issue of fishing permits. The main criticism[44] was that this type of regulation prevented competition between potential investors, monopolizing the resources to the benefit of those who had already established their presence.

Simultaneously, other factors helped to promote a rethinking of the prevailing rules. Among these factors were:

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[43] During the 1960s and 1970s, fishing authorities and the related civil servant staffs seem not to have had the required technical knowledge to implement a stock assessment methodology with enough scientific precision such as to validate, in the eyes of the private fishing sector, a regular enforcement of fishing regulations based on annual catch quotas. In 1980-81, the first systematic stock assessment calculations were made. Despite the annual calculations of these stock assessments during the 1980s, the *suggested* annual quotas were never enforced in the marine fisheries with a greater level of economic exploitation (Northern pelagic fisheries). A few attempts to enforce global quotas in these fisheries during this period faced a successful opposition from private fishing lobbies. We thank the marine biologist A. Zuleta for this information.

[44] This line of arguments was led by a group a economists who had obtained the control of the government bureaucracy. Most of these professionals had post-graduate training at the Chicago School of Economics and from this feature they started to be known as the "Chicago boys".

(i) accumulated experiences around the world showing the failure of free access schemes to protect the economic survival of industrial pelagic fisheries[45],
(ii) a corresponding increasing consensus on the need to combine access restrictions with quotas on harvesting levels[46],
(iii) the increasing economic importance of fisheries for the Chilean economy, as the sector grew rapidly from the mid 1970s until the late 1980s. This growing production started to make fish populations a more scarce resource and, correspondingly, the costs involved in the expansion and future sustainability of the fishing sector became more obvious.

As an outcome of these ideas, in 1978 there was a partial weakening in the historical rights doctrine. The Law Decree No. 2442 led to *free* access. This implied that *all* applications for fishing permits (from resident fishermen) *should* be accepted, if some minimum technical requirements were fulfiled. Free access was promoted by pro-competition economists who had the control of the government bureaucracy. This policy was also consistent with the government's political priority to promote the economic growth of recently reprivatized industries, including the fishing sector, as a way to consolidate a widespread process of reprivatization that took place in the Chilean economy between 1974-1982.

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[45] Until the 1940s, managers around the world did not believe that fishing efforts should be restrained. These beliefs were based on scientific propositions that had prevailed for almost 70 years among marine biologists. Fish stocks were seen basically as free goods (for the period in question, it was probably right to think so). Professor T.H.Huxley in 1884 (then president of the UK Royal Society) wrote for an International Fisheries Conference: "I believe, then, that the cod fishery, the herring fishery, the pilchard fishery, the mackerel fishery and probably all the great sea fisheries are inexhaustible; that is to say, that nothing we do seriously affects the numbers of fish. And any attempt to regulate these fisheries seems, consequently, from the nature of the case to be useless" (Cushing, 1988, page 117).

[46] The shifting emphasis from global to individual catch quotas is a phenomenon that has taken real force only since the early 1980s. (See Scott, 1988).

Law Decree No. 2442 also centralized the responsibility of fishing regulations in a recently created (1976) public regulatory agency (SUBPESCA)[47], which was vested with independent powers in most of the decisions on fishing regulations. The head of this civil service institution, who was and still is second in hierarchy to the Minister of Economics, retained the right to deny fishing permit applications.

In 1978 the *National Fishing Service* (SERNAP) was also created. This is a second public sector agency whose main objectives were centralizing the public sector's statistical records of private fishing activities, monitoring and controlling the fulfilment of the prevailing fishing regulations, and prosecuting any violations. The jurisdiction over these prosecutions came under local police courts. In the Chilean legal system, these courts have lower legal status than Civil Courts[48]. The prevailing fishing regulations at the time defined these Courts' right to fine to violators, but the law did not specify explicit values or an explicit methodology to calculate these fines. Hence, local judges had a significant discretion over the determination of the penalties values.

In order to enable SERNAP's accounting and monitoring tasks, fishing regulations defined the legal obligation, for each fishing boat, to regularly report on the catches of each fishing trip. SERNAP's controlling tasks were to be complemented by monitoring from the Chilean Army and the corresponding local police. Monitoring consisted in random inspections at landing ports and also at marine harvesting zones.

Within the public sector hierarchy, SERNAP was defined as a directly dependent institution under the jurisdiction of the Minister of Economics. However,

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[47] Until then, fishing regulations were under the rule of the Ministry of Agriculture. Under this scheme fishing matters were secondary with respect to agricultural issues, and the ruling of fishing regulations was dispersed among several civil service bureaucrats.

[48] Local police courts are defined in the Chilean legal system as courts with jurisdiction over minor local legal violations (e.g., speeding violations of the traffic law). These courts' jurisdiction over violations of fishing regulations is an indication of the low priority which at the time was assigned to fishing regulations.

due to SERNAP's tasks which are directly related to the control and enforcement of fishing regulations, this definition of hierarchical dependence seems to have produced some problems of coordination with respect to SUBPESCA's policy making and executive powers. On some occasions, these public sector agencies seem to have been involved in conflicts related to which agency was paramount[49].

In the main Chilean fishing grounds, the free access framework prevailed until 1986. In terms of global catch quotas, the suggested, but non enforceable, character of these recommended catch quotas was even more explicit. These suggestions were always exceeded.

The *de facto* ineffectiveness of dispersed fishing regulations[50] was reinforced by a regulation issued in 1980 (Law Decree No. 175) which omitted any explicit mention of global quotas and did not specify a clear commitment to a free access principle. This decree retained the regulator's[51] right to issue fishing permits, but it left this right subject to discretionary criteria and did not specify explicit conditions for the granting of fishing permits.

During the 1980s most of the regulatory decisions continued to be taken on discretionary or case-by-case bases. Different regulatory instruments (e.g., fishing moratoria and minimum catch sizes) tended to be irregular in application, usually following cyclical patterns (some restrictions replacing earlier ones, then to be revoked and replaced by the earlier regulations). Policy changes appeared to be improvisations in the face of 'dangerous' resource levels. This issue deserves a comment.

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[49] Verbal opinions obtained from experienced fishing experts in the functioning of the public sector fishing institutions. Similar disputes, related to hierarchical preeminences, seem to have occurred in tasks jointly carried out between SUBPESCA and the more research oriented Development Fisheries Institute, IFOP (created in 1964).

[50] At this time there was no unified legal piece covering all the relevant aspects related to fishing regulations.

[51] By this we refer to the Director of SUBPESCA.

By 'discretionary' or 'irregular' regulations we mean that the fishing regulatory authorities were systematically unable to enforce policies based on a given set of rules, deriving from previously agreed on, widely accepted, and clearly defined regulatory criteria and enforcement rules. Although the technology of pelagic fisheries and the uncertainty of Nature's states require *flexibility* in the application of regulatory rules, the fishing regulatory authorities' policy objectives and the application of the regulatory policies stemming from them were ambiguous and *ad hoc*.

However, and despite the persistence of discretionary decisions, during the 1980s there were some improvements in the fishing regulation. First, since 1980-81 fishing regulatory agencies started to use more technically qualified staff. This process occurred in parallel to a period of modernization within the whole Chilean civil service sector. Second, during this period, there began a regular calculation of annual scientific stock assessments for the main fish species populations[52]. The use of this instrument helped to formalize the idea of permissible global annual catches. In fact, since 1982 annual global quotas started to be used and enforced in *demersal* fisheries (hake and whiting fisheries) located in the Southern fishing grounds. Third, new regulatory instruments became available: in 1981 (Law Decree No. 458), catch regulations based on minimum sizes for different fish species caught were introduced. This instrument was initially applied to sardine and horse mackerel catches.

From 1982-83, however, there was conflict between fishing regulators and private fishing firms over which instruments were more appropriate to regulate marine industrial fisheries. This controversy was directly related to the increasing scarcity of pelagic species in the Northern fishing grounds, that had been heavily harvested since the mid 1970s. As from that time, the Northern pelagic fisheries became the most contentious fisheries to be regulated. The conflicts were reinforced

[52] Based on the stock assessment methodology known as *Virtual Population Analysis* (see Gulland, 1988).

by the lobbying powers that stemmed from the high concentration and large size of the dominant firms operating in this fishery.

The absence of consensus on regulatory methods led to the increasing use of biological seasonal closures[53] as the main method to regulate fishing efforts from private firms. Seasonal closures were perceived as a more consensual instrument of regulation. As with the use of previous instruments, the fishing regulatory authorities maintained a discretional ruling in the temporal pattern of use for seasonal closures.

Between 1982 and 1986 total industrial catches continued to increase (see Table 3.5). During this period, the fishing regulatory authorities wanted to reduce total harvesting, particularly at the Northern pelagic fisheries. However, the regulatory efforts were unsuccessful. For example, the first (and probably the *only*) serious attempt to *enforce* a policy of global catch quotas, at Northern pelagic fisheries (Law Decree No. 460, october 1981), was unsuccessful: this Decree proposed to enforce a maximum catch quota of 1.3 million tons for sardine annual catches in Northern zone A. Northern entrepreneurs then made lobbying efforts to increase this quota. As a result of these lobbying pressures, a second Law Decree (No. 263, September 1982) increased the maximum permissible level to 1.41 million tons. At the end of 1982, the effective total sardine catches in Northern region A achieved a level of 1.779 million tons. Not one transgressor was penalized. Private fishing firms were successful in obtaining the backing of higher level civil servants.

As a direct consequence of the unsuccessful regulatory controls in the Northern pelagic fisheries, a policy of a *de facto* closed entry was implemented after the mid 1980s. Since 1986 (Law Decree No. 436) until 1991[54], the fishing efforts[55]

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[53] For example, Law Decree No. 160 (1983) was the first to define seasonal closures for sardine catches in the Northern zone A. After 1985 there were regular seasonal closures each year.

[54] More precisely, until the end of 1991 when a new Chilean fishing law was enacted after slightly more than three years of discussions and negotiations. More details at section (3.G).

[55] Defined in terms of the total tonnage capacity of the vessels in operation.

in the main industrial fisheries (pelagic fishing grounds in the Northern zone A and Southern VIIIth region) have been *frozen* at their levels of 1985. This meant, in practical terms, a situation of closed access to these fisheries.

The measure of freezing fishing efforts was adopted as a response to a dangerous (from the fishing authorities' perspective) decrease, since 1981-82, in the stock levels of the main species under exploitation, especially in the case of the Northern sardine stocks since 1981-82 (see Appendix 3.1). Again, during the 1980s global annual catch quotas were *recommended*; yet again, they lacked a real compulsory or enforceable power.

The fishing regulatory authorities were unable to enforce annual catch quotas in the main industrial (pelagic) fishing grounds. Table 3.7 shows, for the main species of the Northern industrial pelagic fishery, the divergence between actual annual catches and those suggested by the fishing regulatory authorities durnng the late 1980s. Table 3.7 shows a *systematic* exploitation over and above the suggested catch quotas. Concurrently, pelagic fish stocks (particularly sardines and horse mackerels) started to show a decreasing trend towards the second half of the 1980s, helping to account for the significant fall in catches during the first years of the 1990s (Table 3.5). Table 3.7 suggests that in Chile there was enough information to predict the decrease in fish stock levels a number of years before it actually affected catch performances. This suggests that the recent fall in catches could probably have been mitigated, if the suggested quotas had been properly enforced.

In the next section we consider why the fishing regulatory authorities did not enforce the suggested annual quotas for Northern pelagic fisheries.

TABLE 3.7
Suggested annual quotas versus effective catches
(Three main pelagic species, Northern Zone A)
(tons, thousands)

	Horse mackerels		Sardines		Anchovies	
	TSC	EC(2)	TSC	EC(5)	TSC(6)	EC(7)
1987	na	279.9	1400(3)	1782.4	na	202.0
1988	89.4(1)	278.7	304(4)	1356.0	50	8060
1989	208.7(1)	265.8	333(4)	1405.1	768.8	13312
1990	na	258.2	na	700.4	na	5997
1991	na	282.8	na	583.3	na	5959
1992	103.3(2)	285.4	35(5)	631.7	na	9821
1993	na	359.9	na	312.6	na	10943

Sources: (1): Barría and Serra, 1989a, (2): Barría and Serra, 1991, (3): CORFO and IFOP,1987, AP 87/6, (4): Barria and Serra, 1989b, (5): Barria and Serra, 1991a, (6): IFOP, 1989, (7): Barria and Serra, 1991,b.

Notes:
TSC: Total suggested (annual) catches.
EC : Effective (industrial fleet) catches.
na : non-available to the author.
Zone A: Regions I and II

- Definition of the TSC:

The criterion for estimating the TSC considers what marine biologists call the "instantaneous coefficient of fishing mortality". This index is an estimate of the ratio between catch and average fish stock. TSC aims at keeping fishing efforts within a level that will allow the survival of a minimum spawning stock, enough to maintain the long run sustainability of the harvesting activity, with the aim of attempting to prevent negative overshooting due to random Nature's shocks or to errors in the stock assessment (Pope, 1984, and Cushing, 1988, p.263). It is a management measure based on a long run stability objective. It is obviously defined by a biologically oriented objective of regulation and conservation.

(3.F) On enforcement weaknesses.

In this section we propose four complementary explanations for the failure or the lack of government's efforts to enforce catch quota policies on many occasions during the last three decades.

(3.F.1) Government's objectives and policy priorities.

Regulators are agents of political principals. It is reasonable to expect that regulatory decisions will be affected by political objectives given that the political principal sets the regulatory agencies' budget. In the Chilean case, the three public sector institutions that are directly related to fishing regulatory tasks (SUBPESCA, SERNAP and IFOP) have budgets that are annually determined by the political authority.

In the case of Chilean fishing regulations, it seems clear that catch quota objectives have been dominated, during most of the period since the mid 1960s, by policy objectives with higher political priority.

During the 1960s the main policy priorities, within the fishing sector, were to promote industrial development and to acquire scientific knowledge on fish populations' behaviour (SUBPESCA-CORFO, 1989). On some occasions resource conservation strategies were promoted by the more technical staff (marine biologists and fishing technicians) working at regulatory agencies[56]. But most of the time these strategies did not obtain enough political support to overcome private sector opposition. This phenomenon is consistent with the commonly predominant view at the time of fish stocks as very abundant resources.

During the 1970s the Chilean economy faced profound economic changes. Parallel to the consolidation of a military dictatorship, a widespread program of liberal pro-market reforms was implemented. This included a widespread process of reprivatization and a significant reduction in the State's direct regulatory role. For

[56] Especially towards 1965-66, after a very rapid expansion period in the harvesting of the Northern anchovy fish stock.

the political hierarchy in control of the government bureaucracy, the dominant economic priorities were to consolidate, through accelerated economic growth, the reprivatization program and the reduction of the State's intervention in economic matters. Under this framework, it is not surprising that fishing regulators could not enforce restrictive catch quota regulations.

During the 1980s resource conservation concerns became more widely shared among different public and private interest groups in Chile, particularly towards the end of the decade. Fish populations started to be increasingly perceived as scarce resources. However, the political group in control of the government bureaucracy (the so-called "Chicago Boys") still preferred, as a general principle, to avoid the direct economic regulations proposed by marine biologists and fishing technicians in response to depleted marine fish populations in the Northern pelagic fisheries. These views did not obtain enough political support. Instead, a more market-oriented policy, transferable individual catch quotas, started to be discussed (section 3.G).

(3.F.2) Institutional organization.

When several regulatory agencies are involved in regulating an industry, conflict can arise from the ambiguous allocations of residual rights of control over the regulatory decision making process. Conflicts of this type will be more frequent, *ceteris paribus*, the lower the priority assigned by the political principal(s) to these decisions. Conflict between regulatory agencies can diminish their regulatory efficiency.

In the Chilean case, problems of this type seem to have occurred between the three public sector institutions directly involved in fishing regulatory tasks. SUBPESCA is the executive and resolutive regulatory agency. SERNAP is formally in charge of information accounting, monitoring and enforcement regulatory tasks. IFOP is the more research oriented agency responsible for providing the scientific information required by SUBPESCA's decision making process.

SERNAP and IFOP are formally subordinate to SUBPESCA. But the latter has no direct control over their budgets. The Director of SUBPESCA is responsible to the Minister of Economics. But the latter is also the principal of the Director of SERNAP. On occasions, this has triggered conflict between SUBPESCA and SERNAP. Budget disputes, and conflicts over decision making preeminence, have also occurred between SUBPESCA and IFOP. These latter disputes seem to have been triggered by significant budget reductions faced by both institutions during the late 1970s and early 1980s, as part of the government's strategies aimed at reducing the State's economic role in Chile.

These conflicts between regulatory agencies can have contributed to the inability of Chilean fishing regulators to enforce more restrictive catch regulations, especially in the Northern pelagic fisheries. But it is clear that this type of problem is closer to a consequence (of policy priorities) than to an original cause.

(3.F.3) Information problems.

On many occasions private fishing firms argued that the regulatory agencies did not have enough reliable scientific knowledge and information on the levels, characteristics and behaviour of the fish populations under exploitation, to formulate an objective and efficient regulation based on annual catch policies. This lack of information, they argued, would probably produce arbitrariness and distortions in the definition of the maximum catch limits.

If a genuine justification for fishing regulations was accepted, incumbent fishing firms usually favoured more direct controls over fishing efforts, such as entry restrictions on additional fishing capacity, fishing moratoria and other minor restrictions over inputs' uses (e.g., type of fishing nets). Most of these regulatory measures would probably have produced smaller reductions in incumbent firms' profits, when compared with restrictive catch quotas.

The "lack of information" argument seems to have had relatively sound bases, at least until the beginning of the 1980s. However, we have already stated that since 1980-81 a process of systematic fish stock assessment calculations was started. The assessment method followed up to date world technology. The quality of the information gathering process upon the catches' age composition, on which the stock assessment methodology is based, steadily improved. The graphs of official (IFOP's) fish stock estimations shown in Appendix 3.1, and the decreasing (since the mid 1980s) actual aggregate annual catches in the Northern pelagic grounds (see Table 3.5), give us a rough idea of the *reasonable* predictive power of these fish stock assessments in terms of anticipating future average catch levels.

Despite the methodological improvements in the official fish stock assessments, private fishing firms argued that there still persisted a significant uncertainty in these estimations. Hence, the incumbent fishing firms' criticisms on the use of quota policies persisted along the 1980s. In section (3.G) we offer a more detailed account of these criticisms, particularly applied to the government's proposal to implement a system of transferable individual catch quotas.

(3.F.4) Regulatory capture.

> "Economists' surveys of fishery regulation make much of the power of government action to remedy the wastes of common property and similar market failures. But I do not believe that an increase in efficiency in resource allocation very often enters into politicians' motivation for intervening in the fishery, or in any other sector... Political support would be given to restrictions on the overapplication of inputs if...they would work to the advantage of incumbent fishermen." (Scott, 1979, pp. 729-730)

Scott (1979) belongs to the so-called "capture" or "interest group" theory that emphasizes the role of interest groups in the formation of public policy. Under this paradigm, economic regulations are understood as often motivated or controlled by the industries to be regulated. This is in contrast with the so-called "public interest" theory that emphasizes the government's role in correcting different types of market imperfections; and where regulatory agencies are viewed as direct benevolent maximizers of social welfare. Classical sources on the "capture" regulatory theory are Olson (1965), Stigler (1971), Posner (1974) and Peltzman (1976). For more details and additional references, see Laffont and Tirole (1993, chapter 11).

In the interest group theory regulatory agencies are usually analysed as facing incentives to identify with specific interest groups. Sometimes these agencies (or their political principals) can behave as simple arbitrators among competing private interests (Peltzman, 1976). On occasions they can be captured by the private parties' interests under regulation (Olson, 1965; Stigler, 1971). But the key common insight is that regulatory outcomes are not independent of the lobbying powers of private groups. The principal-agent relationships that arise from these multiple-tiered power interactions, and the private (rent) stakes that they involve, have their origins in the existence of informational asymmetries. The latter explain why regulators can have discretion and why interest groups have power and stakes.

The repeated inability of Chilean fishing regulators to enforce restrictive catch quotas in the Northern pelagic fishing grounds can be partially explained by "capture" arguments. We already described the economic power of the dominant incumbent firms that have operated in this fishery for at least two decades. We have mentioned the informational uncertainties involved in the attempts to regulate pelagic fisheries. We have also described some of the fishing regulators' informational weaknesses. Finally, it is clear that the common property of marine fish stocks makes distributional disputes an unavoidable and important aspect of fishing regulations.

In fact, fishing regulators need to simultaneously cope with attempting to reduce the allocative inefficiencies deriving from common or incomplete property rights, and also with arbitrating on the distributive disputes that will be triggered by the attempts to regulate harvesting activities. The next section illustrates this type of problems with more detail.

(3.G) The recent discussion on the regulation of Chilean fisheries.

In this section we analyse the late 1980s controversies that arose in Chile as the consequence of two different governments' attempts to enact a new Chilean fishing law. We aim to illustrate some of the complexities involved in the implementation of fishing regulations and, more particularly, the distributional conflicts and resulting lobbying to *capture* regulation when regulatory authorities' attempt to internalize the increasing scarcity values of common pool natural resources.

In December 1989 the military government enacted a new fishing law (the Merino Law). Its formal implementation was intended to become effective as from March 1990. A few days before its introduction, the recently elected Aylwin government proposed postponing the implementation of the new law until October 1990. This proposal was accepted by the newly elected Congress on the basis of a commitment to review the structure of the law. This triggered a protracted discussion of the regulation of fisheries until the end of 1991, after six deferrals in Congress to deal with the proposed bill of reforms. The resulting fishing law was finally approved and enacted in September 1991.

In this section we describe and analyse this process of negotiations over fishing regulations. We proceed as follows. Subsections (3.G.1) to (3.G.4) discuss the three proposed bills of fishing law, their main features, the key controversial issues that stopped them being approved, and the main distributional disputes behind those controversies. Subsection (3.G.5) discusses some lessons on sources of conflict and possible areas for future improvements in the design of regulatory strategies. Finally, we offer some closing remarks.

(3.G.1) The original proposal: the Merino Law.[57]

The Merino Law defined two types of fisheries: those in a stage of *full exploitation* and all the remaining ones. The definition of *full exploitation* was based on biological criteria. A fishery is said to be in a stage of *full exploitation* if exploitation is high enough to offset the "surplus productivity" of the species[58]. The *surplus productivity* of a given fish stock is measured as the difference between recruitment (new individuals that enter the commercially exploitable population) and the natural mortality. Given this definition, the most important industrial fishing grounds were in a stage of *full exploitation* (pelagic species in the Northern zone A and Southern VIII[th] region). These were the most heavily exploited fishing grounds and, accordingly, they were the fisheries that most urgently required changes in their regulation.

Access to fisheries, other than those in *full exploitation*, was to be free, although there was a registration requirement. The crucial innovation of the Merino Law, however, was related to the access regulation for *full exploitation* fisheries. Until then, access to fisheries in this stage was closed by a *freezing* policy on the industrial fleet's cargo capacity (section 3.E). The Merino Law proposed that access

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[57] The name of this proposal stems from the surname of the Commander in chief of the Chilean Navy (Admiral J. Toribio Merino) who initially promoted the enactment of a new fishing law.

[58] This condition simply defines a *constant* fish stock level. If economic exploitation equates or overcomes the surplus productivity of a given fish species, its population remains constant or decreases respectively. The initial level of the fish stock is irrelevant for the definition of *full exploitation* status. This is an odd feature of this definition. However, it seems that the legislator's intention was to keep an explicit ambiguity in this definition. Presumably, the underlying idea consisted of defining a *maximum sustainable yield* (MSY) condition. This idea would correspond with *maximum sustainable* economic exploitation (harvesting). A possible justification for the underlying ambiguity in the formal definition of the full exploitation status could be that it allows the regulator to define in a more flexible way the precise meaning of MSY, for a given fish population. We thank the marine biologist A. Zuleta for suggesting us this interpretation.

to these fisheries be regulated through a system of individual, permanent and marketable licenses for fishing, freely transferable and divisible. These were to be based on *Individual Transferable Quotas* (ITQs) which were defined as a percentage of the annual global quotas (defined in terms of weight caught). The global quota was defined for a "fishery unit" which consisted of a particular fish species and a given harvesting zone. The transferable individual licences gave the right to catch a specific weight (tonnage) of fish.

The original allocation of these ITQs was to be a function of the individual firms' average catches in the three previous years to the implementation of the new law; more precisely, of their percentage share of the corresponding annual catches of those years. This system of allocation was attacked vigorously by representatives of the private fishing entrepreneurs, especially from the incumbent firms operating at the Northern fishing grounds. Recall the dominant presence of the Angelini group in these fisheries.

The initial proposal for allocating transferable individual fishing rights, based on historical presence, ruled out the access of newcomers to a given fishing area[59], unless they were willing to buy fishing rights from incumbent firms. This entry restriction represented a significant cost for the incumbent fishing firms operating at the overexploited Northern fishing grounds, because they were planning to redirect part of their fishing efforts toward the more abundant Southern fish stocks.

Alternative proposals, none of them finally accepted, allowed some percentage of initial participation for new investors, through a public auctioning of part of the global quota. The incumbent firms operating at the overexploited Northern fishing grounds preferred to lobby for free access conditions to the more abundant Southern fishing grounds to the auctioning of ITQs. The incumbent firms succeeded only

[59] The original proposal also included an absolute restriction for licence renting, together with a restriction for individual ownership of 50% or more of the total annual quota of two or more fishery units.

partially in their lobbying strategy. Although a *general* system of free access finally prevailed, Southern fishing grounds were kept under *annually renewable* access restrictions, as long as their fish stocks were classified as fishery units in stage of full exploitation.

The use of ITQs in the regulation of fisheries was encouraged and supported by several Chilean authors, mainly economists. They argued that the main problem at industrial fisheries is one of common property, which creates incentives for an inefficient rent dissipation due to excessive competition among harvesting units. They argued that an efficient way to regulate is through the allocation of private property rights over fish stocks, in order to solve the commonality problem. They also argued that the more traditional global regulations, such as global quotas or fishing moratoria, even though they might solve the biological problem (risk of collapse), they can not solve the efficiency problem, because they do not stop 'excessive' harvesting competition (Bitrán, 1989; Gómez-Lobo and Jiles, 1991; Tasc Report, 1991).

At the institutional level, the Merino Law created a National Fishing Council[60] which was vested with *consultative* powers, while the traditional fishing regulatory authorities (SUBPESCA and SERNAP) retained policy making and enforcing powers respectively.

However, one of the first actions of the recently instated (March 1990) Aylwin's government was a proposal to defer and modify the Merino Law. There were two main *explicit* arguments behind this proposal. First, the new government argued that the originally proposed bill did not include any budget increase to cover the higher costs required to enforce the new regulatory scheme. Second, it was

[60] Formed by representatives of different groups involved in the fishing sector, such as entrepreneurs, workers, fishing experts and civil servants. Membership in the National Fishing Council was an *ad honorem* activity.

argued that the proposed *free access* regime for fisheries, other than those in a stage of *full exploitation*, would imply overfishing and overinvestment in these fisheries.

There was also an important *implicit* argument underlying the government's decision to postpone the enactment of the Merino Law. The ongoing discussion of this proposed bill had resulted in a widespread argument about the constitutional validity of the State's rights to apply and enforce some key regulatory instruments at fishing industries. In particular, the State's rights to limit access to fisheries and to sell property rights over the use of fish stocks were questioned.

Under these circumstances, the new government's diagnosis was that the enactment of the Merino Law could have challenged the fishing authorities' capacity to enforce regulatory actions at industrial fisheries, as this issue had to be adjudicated by the Supreme Court and the Constitutional Tribunal[61]. This possibility was perceived as a significant risk, given that ITQs were the *key* regulatory instrument within the Merino Law. If ITQs were judged to be unconstitutional, the fishing authorities' regulatory capacity would then have been severely reduced[62].

Both the Supreme Court and the Constitutional Tribunal had a *sensitive* political relationship with the new government. The possibility of a political bargaining on this issue, between the executive branch of the government and these other two key judicial institutions, was something that the new government wished to avoid. During this period any constitutional controversy raised delicate issues, because a complex process of political transition from a 16 year military dictatorship to a democratic system was taking place.

The Northern entrepreneurs were not the only private lobby that opposed the Merino Law. Fishing workers' unions also opposed this law but their lobbying

[61] The Constitutional Tribunal is an institution designed with the specific purpose of discussing and suggesting solutions for constitutional controversies.

[62] We are indebted to Joaquin Vial for clarification on this issue (J. Vial was a leading economist in the public sector, among the group of civil servants in charge of the political bargaining required by the final enactment of the new fishing law).

powers had been reduced as a consequence of pro-competition labour reforms which had been implemented since the late 1970s by the military government. Fishing workers' unions argued that the Merino Law implied a "privatization" of the sea, which they opposed. They also feared that this new legal framework could imply higher unemployment because of entry restrictions and smaller catches.

The Northern entrepreneurs opposed the use of ITQs and access limits. Incumbent Southern entrepreneurs were more sympathetic to both types of regulations. This was because they helped to reduce the increasing competitive pressures from the Northern entrepreneurs' desire to reallocate part of their harvesting activities towards the Southern fishing grounds.

(3.G.2) The democratic government's proposal.

After the postponement of the Merino Law, the Aylwin's government prepared its own proposal, trying to include points of view from different groups linked to the fishing sector such as entrepreneurs, workers, fishing experts and related civil servants. In order to do so, a National Fishing Commission was appointed. In order to avoid political conflicts that could damage the recently restored democracy, the newly elected Aylwin's government tried to achieve consensus in most of the relevant political issues. The discussion about a new fishing law was one of these issues.

What differences did this new proposal have with respect to the Merino Law? First, access to all fisheries, excluding those under *full exploitation*, was now to be allowed only with the prior approval of the executive fishing regulatory authority (SUBPESCA), instead of the previously proposed simple registration requirements[63]. Second, the new proposal included more regulatory instruments to regulate fisheries under *full exploitation* than the previous proposal. These included limits on the

[63] Presumably, the approval of the executive fishing authority would be more restrictive concerning access conditions than the previously proposed registration requirements for harvesting at fisheries other than those under *full exploitation*. However, there was no explicit criterion in the bill to be more precise on this comparison.

number of ships, fishing effort regulations, global catch quotas, and ITQs allocated completely via historical rights.

At the institutional level, the enforcement capacity of the fishing authorities was strengthened: their budgets were increased and their rule making powers were retained. This proposal also created one National and several Local Fishing Councils, designed to serve as institutions of discussion and consultation.

Both proposals had important similarities. First, both recognized the need to regulate the fishing activity. Second, both included access limitations and ITQs as important regulatory instruments. Third, both proposals granted rule making and enforcement powers to public sector institutions which were not formally linked to the different private lobbying groups[64].

This new proposal was again attacked by the Northern entrepreneurs. By contrast, Southern entrepreneurs, artisanal fishermen and fishing workers gave their support to it. But this support was not enough to allow the final enactment of this proposal and a protracted multi-party bargaining process started, lasting from 1989 to 1991.

(3.G.3) The bargaining process and the political agreement.

The controversies that arose during the period from 1989 to 1991 were related to four key points:[65]

(a) *Redistributional* disputes about the initial allocation of the exclusive fishing rights, in terms of who were eligible for them, with what proportions of the global quota and subject to what payment for these rights.

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[64] This feature would change in the finally enacted fishing law.

[65] Other minor issues under discussion included the possibility of unemployment costs and the problem of transboundary fish stocks shared with Perú.

(b) *Constitutional* issues concerning the State's right to limit access to fisheries and to sell *full* property rights over fish stocks[66]. The key issue was what type of rights the State has and hence can transfer to private agents over sea resources[67].

(c) Private entrepreneurs[68] argued that an ITQs scheme had infeasible *information* requirements. They argued that regulatory bodies do not, and can not, know the information required to implement an efficient system of ITQs. This criticism is mainly related to the costs of monitoring the true state of fish stocks and, with less emphasis, the individual actions of harvesting firms.

(d) Northern entrepreneurs questioned the whole rationale for fishing regulations. They argued that there was a *cyclical* substitution process among the main species under exploitation, especially between sardines and anchovies. They argued that when one of the species suffers a strong depletion, affecting its basis of reproduction, another species will take up its position in the ecosystem. Therefore, any reduction in a single stock will be counteracted by an increase in another competing species, allowing for continuity in the fishing activity. Moreover, it is asserted that the depleted species will come back after a while, the specific period of recovery depending on the particular species growth patterns and the firms' multispecies harvesting strategies.

The cyclical substitution thesis is still controversial among marine biologists. It is possible to cite partial evidence justifying this case for other fisheries around the world; but no definitive conclusion can yet be drawn (e.g., see Cushing, 1988, and

[66] The constitutional issue has been a common and critical problem in the regulation of fisheries. Comments on the case of U.S. fisheries can be found in Keen (1988) and Fletcher (1965).

[67] For a legal analysis of this issue, see "Informe Constitucional sobre Ley de Pesca" (Constitutional Report on the Fishing Law), December 3rd 1990.

[68] Especially those involved in the Northern fish meal industry. For instance, see *El Mercurio* (January 14th, 1990) for the opinions expressed by Felipe Lamarca, one of the top managers of the Angelini group, the conglomerate that is a dominant firm within this industry.

Gulland, 1988). The key issues are the time period and natural conditions required for such a substitution to take place. Regulators argue that these conditions can be highly uncertain and that therefore the continuity of the fishing activity can also be uncertain.

Northern entrepreneurs succeeded in using arguments (b), (c) and (d) to reduce the use of ITQs and access restrictions[69]. Among the issues under controversy, the constitutional debate became the dominant discussion. In October 1990, the Constitutional Tribunal ruled that several articles of this proposed bill of law on fishing were unconstitutional. The Tribunal's statement was related only to minor legal procedural issues, and did not clarify the main issue of the State's rights to limit access to fish stocks and to sell full property rights over them.

As a result of this ruling, the government was forced to seek a compromise agreement in order to avoid further postponement of the law. By September 1991 a political agreement was arrived at by the main political parties controlling the Congress[70]. The multi-party bargaining problem was finally solved via political procedures, with the legislative branch of the government acting as an arbitrator.

The key aspects of the 1991 Fishing Law actually enacted are:

(i) Substantial restriction of the use of ITQs, compared to the central role they played in the Merino Law. ITQs remained as a possible, though not compulsory, regulation for fishery units under the stage of *full exploitation*. Moreover, the use of ITQs in fisheries under a *full exploitation* regime is limited to a maximum of half of

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[69] In order to gain access to Southern fish stocks, the Northern entrepreneurs wanted to eliminate the fleet (size) freezing regulation imposed by the military government since 1986. An additional way to bypass this regulation consisted in installing new processing plants at the target region, and then defending the need of an own fleet in order to successfully supply the required fresh raw fish. This tactic helped to increase the regional fleet's fishing capacity, despite the formal existence of a freezing policy on its level.

[70] See the amendments to the original new Fishing Law, in Diario Oficial (Official Gazette), September 6th, 1991, Law No. 19079 and Law No.19080.

the annual total catch quota while the other half of the annual quota remains under a free access regime.

This maximum proportion of 50 per cent is supposed to be reached through the annual public sell of 5-per-cent rights over the current annual total quotas. Each year the government can publicly auction individual fishing rights that cannot exceed a 5 per cent of the corresponding annual catch quota for that year. These restrictions imply that the maximum permissible proportion of global annual catch quotas under ITQs is achieved over a period of 10 years. Each ITQ is defined as a specific percentage right over current annual global quotas, whatever be the particular level of the latter. ITQs define transitory fishing rights valid for a 10 year period. Each ITQ right can be transferred to another individual only once a year.

(ii) Two other status for fisheries, known as fisheries *under recovery* (after overexploitation), and fisheries in a stage of *infant development*[71] were created. In these fisheries there is no upper limit to the use of ITQs which are allocated by public auction.

(iii) The law maintained the previous proposal of a National and Local Fishing Councils which are composed of representatives of different interest groups involved in the fishing sector (entrepreneurs, workers, fishing experts and civil servants)[72].

Under the 1991 fishing law these Councils are vested with rule making powers in practically all the most important regulatory issues (see Table 3.9).

(iv) The general regulatory framework maintains free access as the basic principle. Entry restrictions are possible if: (1) the fishery is *under recovery* or in a stage of

[71] The definition of *infant development* and *under recovery* is based on biological criteria. Both types of fisheries represent only a minor proportion of the national fisheries under current exploitation.

[72] Membership to these Fishing Councils is an *ad honorem* activity. There are five Local Fishing Councils, each defined for a different fishing region, and one National Fishing Council. The latter has 20 members. Four of them are representatives of entrepreneurial organizations, four of labour organizations, three are civil servants directly related to fishing regulatory tasks, one is the Director of SUBPESCA, another is an executive secretary who is nominated by the Director of SUBPESCA.The other seven members are directly nominated by the President of Chile.

infant development; or (2) the fishery is in a stage of *full exploitation*. A technical report from the fishing regulatory authority (SUBPESCA) and the approval of at least two thirds of the National and Local Fishing Councils are required in either case.

In case (2), entry restrictions are formally allowed only as a *transitory* device. Entry restrictions, for that part of the global quota which is excluded from the ITQ mechanism, are possible but with a time limit of one year. However, the fishing authorities can each year propose a new one year extension of the entry restriction.

(v) Finally, the law retains (1) annual global catch quotas and (2) other biologically oriented controls on fishing efforts (seasonal closures, minimum net sizes, and minimum catch sizes) as the core instruments of control.

(3.G.4) Possible sources of distortion in the current fishing law.

Table 3.8 shows the main features in the evolution of the recent discussion on the Chilean fishing law. Rows show the three different legal proposals, and columns describe the access regimes, the main regulatory instruments and the decision making mechanisms contained in each proposal. Table 3.9 shows in more detail the different decision areas and the corresponding legal requirements for the 1991 Fishing Law. In what follows we pinpoint three possible sources of distortions or imperfections within this legal structure:

(i) Available regulatory instruments and their enforcement.

The current legislation is basically *free access* oriented and the main regulatory instrument consists of *global* catch quotas. Empirical evidence has shown that these two instruments are ineffective and also inefficient in solving the *overfishing* problem, both from the biological and economic perspective[73]. The impact

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[73] Surveys and case study analyses which describe the inefficient resource allocations that result from fishing regulations based on global instruments of harvesting control and direct controls over fishing efforts, can be found in Munro and Scott's (1985) and Munro's (1982a) surveys of Canadian fishing regulations. See also the multi-country descriptions in Charles (1988), Townsend (1990) and Copes (1986) and the case studies in the special issues of two specialized journals in fishery economics: the *Marine Resource Economics*, Vol. 5, No. 4, 1988, and the *Journal of the Fisheries Research Board of Canada*, Vol. 36, No. 7, 1979.

of regulation will depend on the fishing regulator's effective powers to enforce the available instruments when the regulatory decisions involve costly adjustments for incumbent firms. The regulator's enforcement powers are directly related to the support of his political principals. Budgetary decisions are a key aspect of this support. Since the enactment of the 1991 fishing law, both SERNAP's and SUBPESCA's budgets have increased in real terms (above inflationary indexation). However, the enforcement productivity of this additional financing still remains to be evaluated.

Beside budgetary issues, the new fishing law offers some scope for improvement, versus the previous legal framework, in the organization and implementation of the fishing regulator's enforcement actions.

First, SERNAP's monitoring and controlling tasks are supported by private fishing firms' legal duty to register in a National Fishing Register, in which they have to report technical aspects of their fishing fleet. Each fishing boat also must give information on its catch in each fishing trip. Processing plants must regularly provide information on their use of raw fish catches and their suppliers (boats).

This makes it possible to cross check the validity of boats' catch reports. SERNAP now has the opportunity to change its traditional policing-type approach, placing now more emphasis on auditing given the possibility of cross checking between boats' direct catch reports and the processing plants' production report duties. As we mentioned before (section 3.E), SERNAP's traditional approach to regulatory enforcement has consisted in checking boats' catch reports by performing random policing visits to landing ports and harvesting areas. Now the policing task must also be extended to processing plants[74]. Refocusing enforcement efforts towards more auditing probably requires budgetary increases for SERNAP. The resulting

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[74] SERNAP is also attempting to implement a monitoring system which consists of satellite control upon boats' harvesting actions.

combination of policing and auditing efforts will affect the efficiency of enforcement[75].

Second, violations of fishing regulations and other related legal duties are now penalized, for the first time, by clearly defined fines. The new fishing law contains an explicit section (*Title IX*) defining a range of non-monetary penalties[76] and graduated monetary fines for different types of transgressions.

The graded system of monetary penalties makes the fine a proportion of the catch value. More precisely, different proportional factors, according to the severity of the infraction, are applied to "infraction values" which are defined by multiplying the catch tonnage under violation and the unit value (landing beach price) of the species caught[77]. The dependence of the fine level upon the catch value provides more efficient penalty incentives than fixed penalties (Stigler, 1970; Posner, 1986).

Finally, the legal jurisdiction over prosecution cases against violators of the fishing law rests with the Civil Courts. They are more powerful tribunals than the local police courts which were previously in charge.

(ii) Scope for the use of ITQs.

Even though the use of ITQs is possible, it is limited to a maximum of half of the global annual quota at fisheries under *full exploitation*. There seems to be no

[75] Two interesting institutional analyses of enforcement problems of fishing regulations can be found in Clark, Major and Mollett (1988) and Anderson (1989).

[76] For instance, the closure of processing plants, the appropriation of the tonnage caught and/or fishing equipments, the caducity of boats' fishing permits and fishermen's individual fishing licenses.

[77] For example, violations which are classified as "severe" imply: (a) a monetary fine which can vary between 3 to 4 times the corresponding *infraction values*. The Civil Judge determines, within this range, the specific proportional factor to be finally used. The legal responsibility to pay the fine falls on the material author of the infraction. (b) The captain of the industrial boat that violates the law is also personally penalized by fines that can vary between (Chilean pesos) values which are equivalent to a range of US $1400-15000. (c) 3 months suspension periods for fishing licenses of captains whose boats have been proved to commit *severe* violations, and the permanent cancellation of the captain's fishing license if a reiterative violation is proved. The law includes within the category of *severe* violation, among other infractions, the absence or untruthful submission of the boats' regular reports on each fishing trip's catch productivity.

clear-cut *technical* justifications for a partial use of the ITQ instrument. The 'biomass information requirements' argument does not justify it because there are no significant differences in the biomass information required to apply either the global quota or the ITQ system. On the other hand, the argument that the enforcement of ITQs would be very costly (to be efficacious) seems to be not very strong. Not if we at least compare this cost with the enforcement costs of annual global quotas. Moreover, some authors (e.g., Gómez-Lobo and Jiles, 1992) have argued that the enforcement of ITQs should not be too costly, given that most of the fishing production is exported and hence there is a complementary way, to direct controls on individual catches, in controlling and enforcing the ITQs. The complementary enforcement could make use of monitoring devices based on export statistics.

A plausible explanation for the restricted scope of ITQs is that it is a compromise to the lobbying pressures that were triggered by the disputes over the initial allocation scheme for the ITQ rights. Given this compromise solution, it is probable that ITQs, if they are used, will not control all rent dissipation.

The new fishing law does not define whether the owners of ITQs have the right to harvest before (a first mover advantage) the other firms which harvest under free access conditions, or whether both types of fishing schemes have to simultaneously compete in harvesting. In either of these two cases, it is not clear *a priori* how the regulator will be able to enforce the catch quota limits. Also, in both cases each fisherman with ITQs has the incentive to harvest early to fill his quota when fish is still relatively abundant and costs are relatively lower. The resulting rush and investment in capital and labour inputs raise the aggregate costs of landing the allowable catch. This type of harvesting incentive becomes stronger the shorter the temporal advantage firms with ITQs have over the firms that harvest under free access conditions.

(iii) Rent seeking behaviour.

Another potential source of problems is related to the decision making mechanisms and their influence on the fishing regulator's enforcement. The new fishing law gives partial resolutive powers to private lobbies[78] whose objectives may differ from the social ones. These powers might strengthen the rent seeking efforts of these lobbies. It is not obvious, however, that all private sector's representatives will necessarily collude against the fishing regulator. It is even possible that a wider private participation in the regulatory decisions can bring more credibility and institutional stability to fishing regulations. More precise comments will have to wait for more empirical evidence on the operation of this new fishing law.

At the time this chapter is written, the 1991 Fishing Law will have been in operation for almost three years. During this period, we have observed some promising improvements in regulation. For instance, the successful application of ITQs in the case of the red shrimp (*pleurocondes monodon*) (Calfucura and Jiles, 1994); also the combined application of (a) seasonal closures and (b) individual catch permits, when harvesting is allowed, in the case of the Chilean abalone (*concholepas concholepas*)[79]. In both cases, the current legal framework has made it possible to arrive at promising solutions as an initial step in a situation of biologically overdepleted fish populations.

However, ITQs are still not applied to the most conflicting fisheries, that is, the pelagic fishing grounds in the Northern zone A and Southern VIIIth region. Both fisheries are still kept under (annually renewable) closed entry regulation and subject to regular seasonal closures.

[78] See footnote 72 and Table 3.9.

[79] In this case an official Register has been created which lists the authorized fishermen in this *artisanal* fishery. Membership in the Register gives the right to an individual fishing permit. New entry to the official Register has been closed since the start of this new regulatory program. To obtain membership, when the program started, fishermen had to fulfil some technical and legal conditions which are subsequently enforced by local fishing authorities. When harvesting activities are allowed, the fishing regulatory authority (SUBPESCA) announces a total catch quota for that harvesting season. The global quota is then automatically divided by equal parts among the valid members of the Register. Between 1993-94, harvesting seasons have been opened twice each year, each time for periods of approximately 4-6 weeks.

TABLE 3.8
Evolution of the recent discussion on the Chilean Fishing Law

	Access regime and regulatory instruments	Decision making mechanism
Law No. 18.892 (The Merino Law) (Dec. 1989)	1) **Full Exploitation Fisheries:** - Limited access, conditioned by the use of ITQs allocated via historical rights(75%) and public auctions (25%). 2) **Other Fisheries:** - Free access, simple registration is required.	- Declaration of full exploitation stage and auctioning of ITQs require technical approval from SUBPESCA* (resolutive power), and an expert report from the National Fishing Council (consultative power).
Aylwin's Government Proposed Bill of Law (July-Sept.1990)	1) **Full Exploitation Fisheries:** - Limits on number of ships. - Fishing effort regulations. - Use of ITQs allocated only via *historical rights*. 2) **Other Fisheries:** - Entry permission from the fishing authority is required.	- SUBPESCA has full resolutive rights, and the National Fishing Council has only consultative powers.
1991 Law (Sept.)	1) **Full-Exploitation Fisheries:** - Free access, unless the fishing authority states the contrary (see decision mechanism). - Limitation of access means to put a limit on the fleet's tonnage capacity. - Possible but not compulsory use of global catches quotas. - Possible but not compulsory use of ITQs, restricted to only a maximum of 50% of the global annual quota. Each year only 5% of the global annual quota can be auctioned. 2) **Two other fisheries' status** are created: fisheries "Under recovery" and in "Infant development": - Use of ITQs on catches, allocated completely via public auctioning[80]. 3) Other Fisheries: ("**traditional**"). - Fishing permit requirements.	- SUBPESCA can declare a fishery in stage of full exploitation, and auction ITQs, with the approval of both the National and Local Fishing Councils (absolute majority required). - SUBPESCA can close access to fisheries under full exploitation stage with approval of two thirds of the National and Local Fishing Councils. - SUBPESCA can set annual global quotas with the approval of the majority of the National Fishing Council and upon consultation to the Local Fishing Council. - SUBPESCA can auction ITQs in fisheries "under recovery" and in "infant development" with the approval of the majority of the National Fishing Council and upon consultation to the Local Fishing Council.

SOURCES:Fishing Law, Tasc Report (1991), Jiles (1992). For more details on the 1991 Fishing Law, see Table 3.9.

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[80] In the case of the *infant development* status, 10% of the global quota *can* be allocated through *historical rights*.

TABLE 3.9
Decision making mechanisms in the 1991 Fishing Law

Decision Area	Requirements for legal approval	Remarks
(I) Declaration of *full exploitation* stage:	- Fishing authority's technical report. - Absolute majority in Local and National Fishing Councils.	
(1.1) Access restrictions	- 2/3 members approval in Local and National Fishing Councils. - Fishing authority's technical report.	- Access restrictions are transitory, with a maximum duration of one year. However, they can be extended each time by one more year.
(1.2) Return to the *general access* regime.	- Absolute majority in Local and National Fishing Councils. - Fishing authority's technical report.	
(1.3)Global annual quotas	- Fishing authority's technical report. - Consultation with Local Fishing Councils - Absolute majority in National Fishing Council.	- If unexpected favourable natural phenomena occur, it is possible to increase the global quota with the approval of National Fishing Council.
(1.4)ITQs	- Absolute majority in Local and National Fishing Councils. - Fishing authority's technical report.	- If ITQs are auctioned in a year, access to the fishery is closed that year.
(II) Declaration of *under recovery* stage and ITQs (*)	- Fishing authority's technical report. - Consultation with Local Fishing Councils. - Absolute majority in National Fishing Council.	- If this stage is declared, previous fishing permits are finished. - During first year, 100% of the total annual quota is auctioned.
(III) Declaration of *infant development* stage and ITQs (*)	- Fishing authority's technical report. - Consultation with Local Fishing Councils. - Absolute majority in National Fishing Council.	- If this stage is declared, special transitory permits (for three years) are given to those fishermen already established in the fishery. After that, a new fishing permit is given for ten years more. - If there are fishermen previously established in the fishery, 90% of the global annual quota is auctioned. On the contrary, the whole quota (100%) is auctioned.

SOURCE: Current Fishing Law.

(*) The declaration of this stage triggers the option to use ITQs.

Despite the uncertainties involved in the future performance of this new regulatory framework, there are some lessons that can be drawn. This is what we examine next.

(3.G.5) On sources of conflict and areas for improvement.

(3.G.5.a) Institutionalizing the increasing scarcity of common pool resources

History teaches us that the creation of private property is an endogenous and gradual response to the increasing scarcity value of common pool resources originally treated as free goods[81]. However, private property rights are not always the optimal (least costly) institutional response to the increasing scarcity value of these resources. The use of private property can sometimes involve significant costs. Private adjustments in the optimal size and structure of the productive firms are an alternative response, as are private contractual arrangements between firms. Regulatory schemes and the corresponding legal rules are another option. Which will be the optimal solution for internalizing the increasing scarcity values depends on industry specific conditions.

The constitutional controversy that arose in Chile with respect to the State's rights to control access to marine fish stocks and to assign and sell full property rights over them suggests the need to consider the efficient evolution of the legal status of originally free available resources that change their scarcity values over time and hence their alternative economic costs. Legislators need to define in a more precise way the State's rights over these matters. This issue has far more general applications than fishing industries.

In fact, this is a classical example of problems that legislations face when originally free goods, or public goods which are not subject to congestion, are transformed by increasing use into scarce resources. Externalities in consumption (air and water pollution) or 'rival consumption' goods subject to commonality problems (fish stocks) are only two examples.

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[81] See, for instance, Libecap (1989), North (1990) and North and Thomas (1973).

(3.G.5.b) Short run versus long run aims

Any regulatory framework faces the problem of formulating two types of strategies. One is choosing the most efficient instruments when the regulated sector is approaching expected long run industry's patterns. The other type involves regulatory policies related to undesired short run disequilibria; for instance, when a government decides to buy out a given percentage of an overcapitalized fishing fleet which is in the hands of the private sector.

The temporal distinction between these types of regulatory strategy should give a insight into the short run negotiations between regulators and the private sector. It seems wise to divide the regulatory discussion between, first, trying to achieve an agreement on what is desired in the long run (*aims*); and second, how we wish to and can approach that situation (*means* and short run targets). This negotiation strategy may reduce the likelihood of getting trapped in vicious circles of disagreement, especially when the rates of temporal discount are high (as they normally are in developing countries) and the stakes under dispute are significant.

(3.G.5.c) Distributive disputes

Any regulation that restricts access to a valuable resource, which up to then has been freely available, is likely to give rise to socially costly distributional disputes. Regulators have to be prepared to arbitrate among the competing claimants.

The distributional issue was clear in the recent Chilean controversy over fishing regulations. Consider the Northern entrepreneurs's strong and systematic opposition to ITQs proposals and access restrictions. Their opposition was one of the main causes of the dismissal of the first two proposed bills.

There are no clear technical reasons to justify the different ITQ regulations that were finally enacted and accepted for fisheries under *full exploitation*, versus those *under recovery* or in *infant development*. However, there exists a clear and important asymmetry between both types of fisheries. Only in fisheries under *full* *exploitation* status were there long-established firms, with significant harvesting levels and with strong lobbying powers.

In these fisheries the prospect of losses, triggered by a more widespread use of payment schemes to enjoy exclusive private harvesting, was clearly more threatening for the incumbent firms. This perception of ITQs, by Northern entrepreneurs, was reinforced by the overdepleted state of the Northern fish stocks and the resulting desire of these firms to reallocate their harvesting operations more intensively in the Southern fishing grounds. This specific feature helps us to understand the recent Chilean failure in allocating fishing property rights based on historical presence, despite the economic literature suggesting this allocation device as a possible solution for the distributional disputes (see, for instance, Cropper and Oates, 1992; Libecap, 1989).

When a country needs to institutionalize higher social scarcity values for originally common pool resources, the regulatory authorities must be prepared to deal with the policy challenges that can be triggered by the probable disputes about the distribution of the income effects. From the regulator's perspective, the central element of these challenges consists in helping to agree on and design Paretian compensations for the losers that can emerge from the institutional recognition that the common pool resource no longer has a zero shadow scarcity value.

The design of these compensation schemes must overcome two important obstacles. First, there is a clear difficulty in attempting to assess the relevant value of the costs and benefits that result from the regulatory changes. This is particularly so at marine industrial fisheries, where firms' net income flows are affected by uncertainty on Nature's states and rivals' actions. A clear corollary for fishing regulatory authorities is the need to persevere with investments in information gathering concerning the fishing sector. A second key obstacle relates to the regulator's credibility to fulfil and to enforce the promised compensation schemes, once the new legal institutions have been set up. In order to make headway on this issue, the regulatory authority needs to avoid discretionary policy improvisations[82].

(3.H) Final remarks.

(3.H.1) Scope.

This chapter has not attempted to give a complete review of Chilean fishing regulations. There is a whole set of more technical measures which have not been mentioned in detail: seasonal and geographical closures for fishing activities; input restrictions, such as regulations on fleet's harvesting capacity, or restrictions on the type of gear and fishing nets, and restrictions on minimum catch sizes, among the most important ones. A proper discussion of each of these instruments would take up too much space. Our emphasis has been placed on *access schemes* and *quota devices*. Both instruments deal directly with the problem of common property which is at the heart of the fisheries issue.

In the analysis of these instruments we have emphasized the regulatory problems that usually arise from the conflicting interests and bargaining strength of the private parties affected by the regulatory changes and the triggered modifications of formal or informal property rights.

(3.H.2) Story of Chilean fishing history.

In Chile fishing regulation to solve common pool problems has generally taken second place to public policy tasks with higher political priority. These included the promotion of industrial development during the 1960s; and during most of the 1970s and until the mid 1980s, reprivatization and reduction in the State's direct regulatory role. This ranking of political priorities helps us to understand the persistence of enforcement weaknesses in fishing regulations.

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[82] Policy *credibility* is a fashionable topics in the current literature on macro policy. See, for instance, Persson and Tabellini (1990), Alesina and Tabellini (1988) and Barro and Gordon (1983).

The persistence of a second place ranking for fishing regulation can be partially understood as the result of a relatively high abundance of Chilean fish populations, particularly before the growth of the fishing sector in the mid 1970s. It is also plausible to argue that the resulting low policy profile for restrictive catch regulations could have been partly the result of *regulatory capture*. We have described the economic and political importance of the conglomerate that has direct control over a significant proportion of the fishing industry in the Northern pelagic fishing grounds where most of the disputes arose.

Some of the peculiar features (section 3.G.4) of the new fishing law that emerged from the recent Chilean controversies over fishing regulations support the arguments of regulatory capture. This conjecture confirms the importance of the disputes that are usually triggered by regulatory authorities' attempts to restrict access and to regulate the increasing scarcity values of common pool marine fisheries.

(3.H.3) Distributional conflicts: feasible regulations.

The recent Chilean controversy over fishing regulations highlights the importance of transaction costs based regulatory constraints when a government (or the interest groups that elected that representative body) aims at improving the economic efficiency of a given institutional arrangement. In the Chilean case, distributional disputes over the fishing regulations were a binding regulatory constraint because it was costly to design side payments or Paretian compensation schemes for the potential losers. These compensation schemes were a costly or binding mechanism design problem for the government because the negotiations faced significant transaction costs. The sources for these transaction costs can be traced out, and related to, asymmetric and incomplete information sets. This is a lesson already established in the increasing literature on informational economics (see Gravelle and Rees, 1992, chapter 22; Laffont and Tirole, 1993).

A clear corollary that arises from this lesson is the misleading welfare evaluations that can result from using first-best optimality prescriptions. The possibility of misleading conclusions is directly related to the presence of significant transaction or informational costs. When transactions are not informationally costless, welfare prescriptions must consider *constrained* optimality yardsticks (see, for instance, Arnott and Stiglitz, 1986; Farrel, 1987) which take account of the relevant constraints on information sets and the feasible regulatory instruments which are available to the regulatory authority.

In terms of the regulation of common pool resources, this general principle implies that regulators cannot expect to eliminate the distributional conflicts that arise from restricting entry and introducing positive pricing for the use of these resources. The regulators' objective should be to reduce these conflicts, while simultaneously aiming to obtain some partial (*constrained*) improvement in the pricing of the common pool resource.

Given these distributionally oriented constraints, a relevant criterion in the evaluation of alternative regulatory instruments should therefore be that the chosen instrument(s) can be implemented and enforced without causing too disruptive or socially costly conflicts. If conflicts persist, the authorities' efforts should then be devoted to reduce the informational asymmetries which lie at the origins of the unsettled distributional disputes.

(3.H.4) The 1991 Chilean fishing law.

Despite the binding constraints on the fishing regulator, that resulted from the political solution arrived at for the distributive disputes among the different private interests involved in the recent controversies, it is plausible that the new fishing law offers the possibility of net allocative gains when it is compared with the previous legal setting.

First, the main achievement from the recent reforms is the creation of a more unified and more coherent regulatory framework. Over time this benefit probably outweighs the specific imperfections that we have already mentioned with respect to the new fishing law. In fact, all these imperfections are avoidable or subject to gradual improvements. Increasing empirical evidence on the effective operation of this new fishing law can help to advance in this direction.

However, to do so requires that this more coherent legal setting generates more consistent and hence more credible fishing policy decisions. This requires a two-sided balance: on the one hand, the fishing authorities' credible commitment to fulfil and enforce the policy aims and legal procedures which are considered by the new fishing law; on the other, the private sector's credible commitment to abide by and cooperate with the decision making mechanisms and the enforcement of the agreed on regulations.

A more cooperative interaction between the regulatory authority and the regulated firms would probably help to reduce the transaction costs which are derived from informationally costly distributional disputes. Lower transaction costs tend to increase, *ceteris paribus*, the efficiency in the enforcement of regulatory aims. The private sector's participation in the decision making process of several key regulatory decisions may help to improve the outcomes from such interactions. However, the final result will depend upon the magnitude of the distributional pressures which will be triggered by new regulatory efforts to internalize the increasing scarcity of the more depleted common pool fish stocks.

There exists a second line of arguments that leads us to expect a more efficient performance from the current fishing law compared with earlier experiences. These arguments refer to the circumstances under which the new law was finally enacted.

First, this law arose after a long and widespread discussion on fishing regulations. This had not occurred in Chile, at such a scale, in the previous two decades. As a consequence this discussion has produced a partial improvement in the understanding of the key issues subject to controversy.

Second, for the first time over a long period, the issue of fishing regulations was perceived as a national problem with 'high' political priority: the new fishing law was the first main law enacted by the recently elected democratic government, after 16 years of military dictatorship.

Third, the long controversy tended to produce a more widespread perception that some of the key Chilean fish stocks are scarcer than in the previous decades.

However, it still remains to be seen if the three latter arguments will effectively translate themselves into future stronger political support for the enforcement of binding catch regulations, especially when they affect incumbent firms with significant lobbying powers. The relevance, in the recent past, of arguments in the line of regulatory capture lead us to be cautious. It may be worth to quote one of the conclusions of Libecap's (1989, p.3) study of contracting for property rights: "...both economic theory and history provide reasons for believing that the net social gains from changes in property rights at any time will be quite modest."

(3.H.5) Other countries' experiences.

The Chilean experience in regulating marine industrial fisheries does not differ qualitatively from the main problems that fishing regulators have also faced in other countries. The economic literature on common pool marine industrial fisheries[83]

[83] Three analyses of problems of contracting for property rights at common pool natural resource sectors, including the analysis of attempts to regulate access and to enforce catch quotas, are Libecap (1989), Eggertsson (1990) and Ostrom (1990). These three studies combine theoretical principles with information on different in-depth case studies. While the former two include analyses of small-scale artisanal as well as marine industrial fisheries, Ostrom's study basically concentrates on small-scale common pool resource sectors. As a consequence of this, Ostrom puts greater emphasis upon the possibilities for successful self-organized collective actions aimed at improving the economic exploitation of these resources. For additional detailed institutional analyses of the regulatory problems encountered at common pool marine industrial fisheries, see Swanson (1992) and, especially, Wise (1984) and Miles (1989).

describes a general trend towards a prolonged persistence of open access and common property conditions, as the result of the existence of[84]:

(i) high exclusion costs, especially for migratory fish species,

(ii) high internal governance costs among the fishermen with access to the common pool resource; for instance, think of the problems to self-organize collective regulatory actions among numerous fishermen with heterogeneous fishing skills, and

(iii) a long-standing legal protection, enforced by the state, of open access to fisheries by all citizens (most of the times with justification on equity grounds). The case of US fisheries is widely mentioned as an example of this latter point (Libecap, 1989 and Eggertsson, 1990).

Libecap (1989), Wise (1984), and the series of papers in Miles (1989)[85] are also particularly clear in emphasizing the importance of the regulatory constraints that arise from the distributional disputes triggered by the restrictions on access and catches that fishing regulators attempt to implement and enforce. Related to this, Libecap (1989) concludes that:

(iv) the *concentration* of the current and proposed distribution of the rights to exploit the common pool resource, and

(v) the informational asymmetries that surround the negotiations of those rights among the affected parties,

are factors that, added to (i), (ii) and (iii), create new sources of problems that tend to intensify the distributional disputes triggered by changes in property rights.

However, as the common pool losses (rent dissipation) increase so do the gains from additional access restrictions. Therefore, the accumulated experiences around the world also show (as in the Chilean case) a gradual, but still socially costly in terms of distributional disputes, evolution from free access towards regulations based

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[84] The quoted taxonomy is best described in Eggertsson (1990, chapter 8).

[85] Among this series of papers, Gulland's essay offers particularly clear insights.

on entry restrictions, improved enforcement of individual fishing licenses and direct controls on incumbent firms' fishing efforts, and afterwards towards global catch quotas.

Each new control on fishing effort and catch restriction has tended to face opposition from incumbent firms. But the increasing depletion of fish populations led these firms to finally benefit and hence accept the collective global controls. However, there is ample evidence that despite the use of global instruments of control a serious inefficient rent dissipation continues. It is also true that each of these regulatory instruments has specific advantages as well as disadvantages, where the net balance between them is usually highly specific to the individual fishery[86]. As Ostrom (1990) emphasizes, industry specific institutional details are very important in the analysis of changes in the property rights of common pool natural resources.

In some cases, most of them since the mid 1980s, the slow evolution of property structures in marine industrial fisheries had led to the successful enforcement of individual catch quotas. Some examples are the cases of marine industrial fisheries in Iceland (herring fishery; ITQs since 1988), Australia (bluefin tuna fishery, a transboundary fishery that is shared with Japan and New Zealand; ITQs since the early 1980s) and, especially, New Zealand (since 1986, New Zealand has the most complete system of ITQs in the world, covering the regulation of 32 fish species)[87].

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[86] For example, despite the generalized criticism with respect to the inefficiencies of using global fishing regulations, there are some cases where their use seems to have produced reasonable regulatory results. Along this line, Gomez-Lobo and Jiles (1991) quote the case of the Japanese regulation for offshore migratory species fisheries, where global catch quotas are combined with boat-specific fishing licenses. We were not able to find detailed information about the specific institutional details involved in this case.

[87] For original references, see Gomez-Lobo (1991), Scott (1988), Eggertsson (1990). For a detailed account of the case of New Zealand, see Clark, Major and Mollet (1988).

All these cases share the important common feature that ITQs were finally implemented and successfully enforced, despite the original opposition from incumbent firms, after a feeling of *crisis* (meaning a severe deterioration of the catch per unit of fishing effort) was perceived and accepted on an overall basis by the main economic agents involved in the regulatory negotiations.

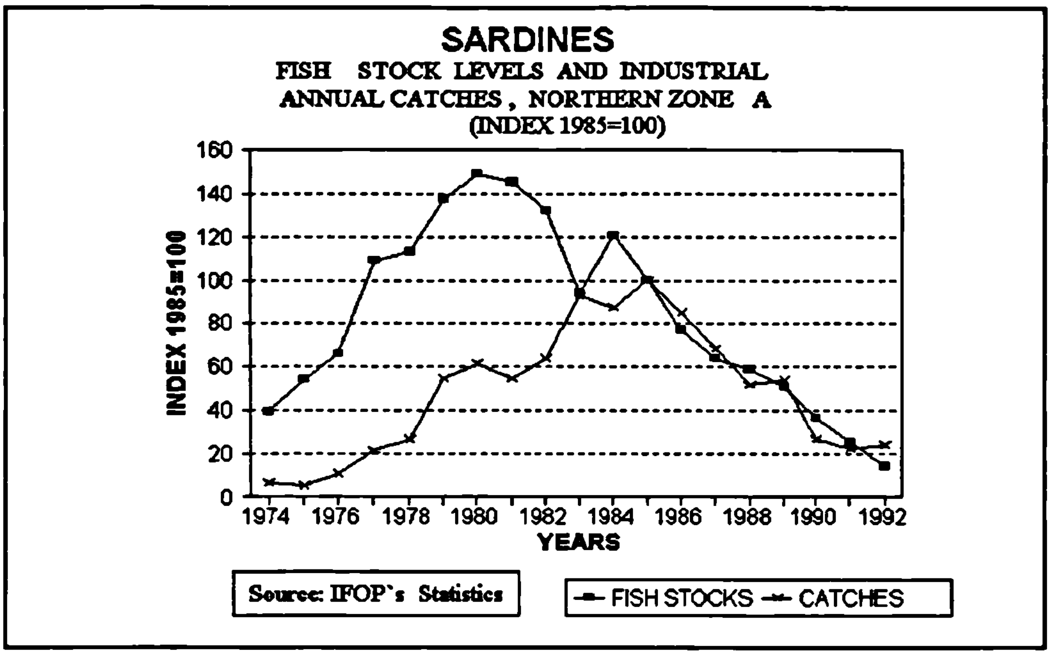
In the successful case of New Zealand, historical rights were used as the key criterion for the initial allocation of ITQs (this is a common feature with the other successful implementations of ITQs). ITQs were defined as permanent rights over an *absolute* catch tonnage with the aim of minimizing firms' opposition. An enforcement system, based on cross-checking audit techniques, was implemented (the new Chilean enforcement system for catch controls is based on this experience). A national fish quota trading exchange was created with the support of public and private institutions.

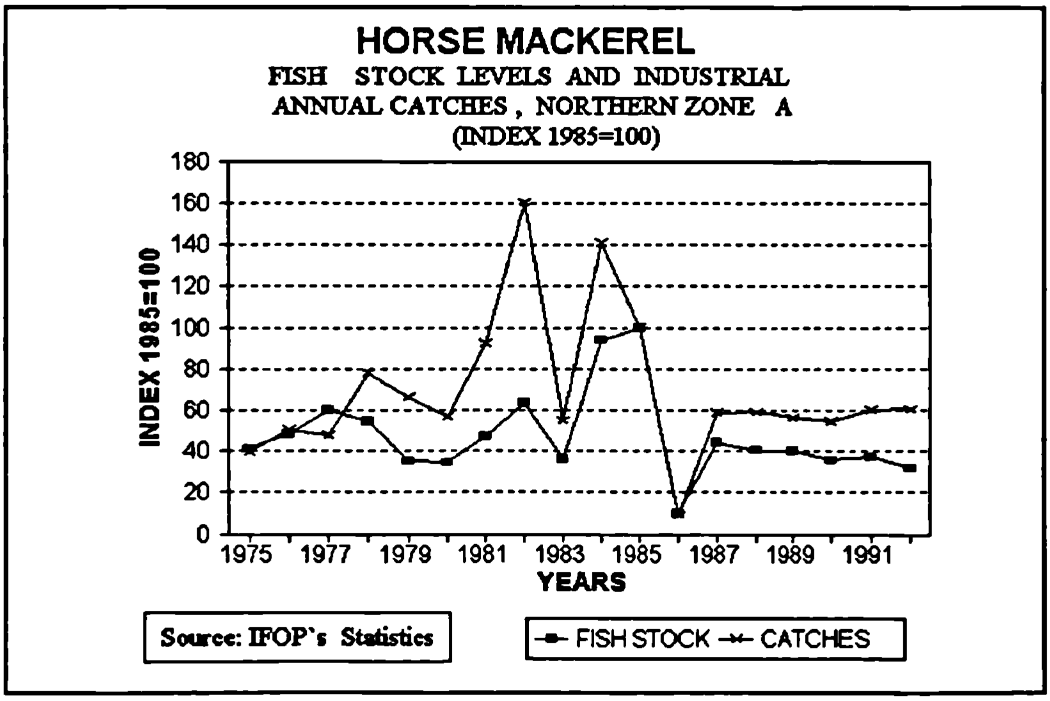
Using the latter institution, at the start of the ITQs system the government bought back a proportion of ITQs from private firms so as to reduce the total fishing efforts and aggregate catches. The government's budgetary capacity to do so was an important factor, according to Clark, Major and Mollet (1988), in contributing to the initial success of this ITQs system.

The latter point is again related to the key influence of distributional issues on the fishing regulators' policy-making. This is consistent with the story of Chilean fishing regulations, which confirms the vision of property rights changes as endogenous and politically determined collective responses to the changing scarcity net values of originally common pool resources. The concept of "net" values not only considers traditional production costs, but also takes into account the exclusion, governance and enforcement costs which are directly related to the implementation of more complete property structures.

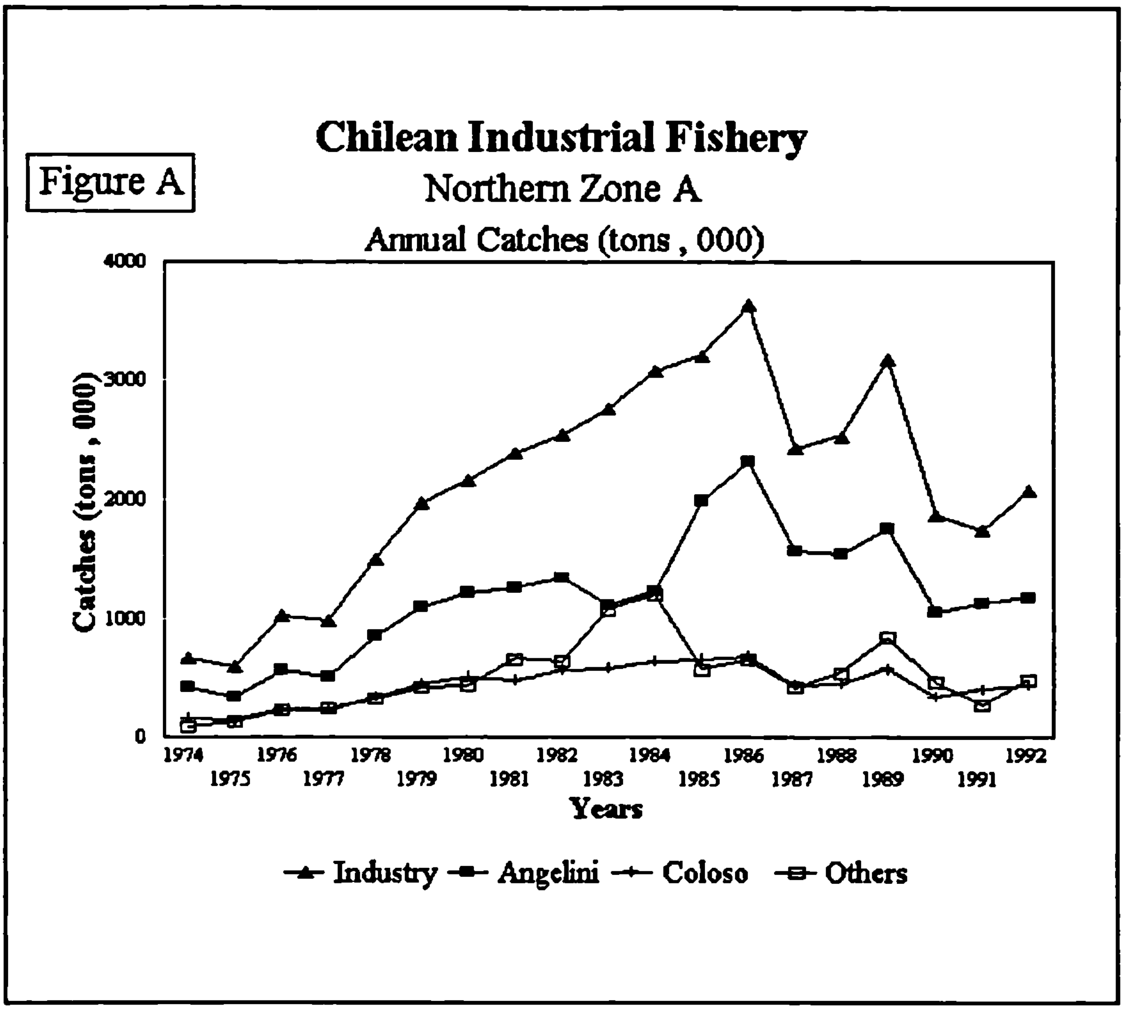
(3.J) Appendices

Appendix 3.1

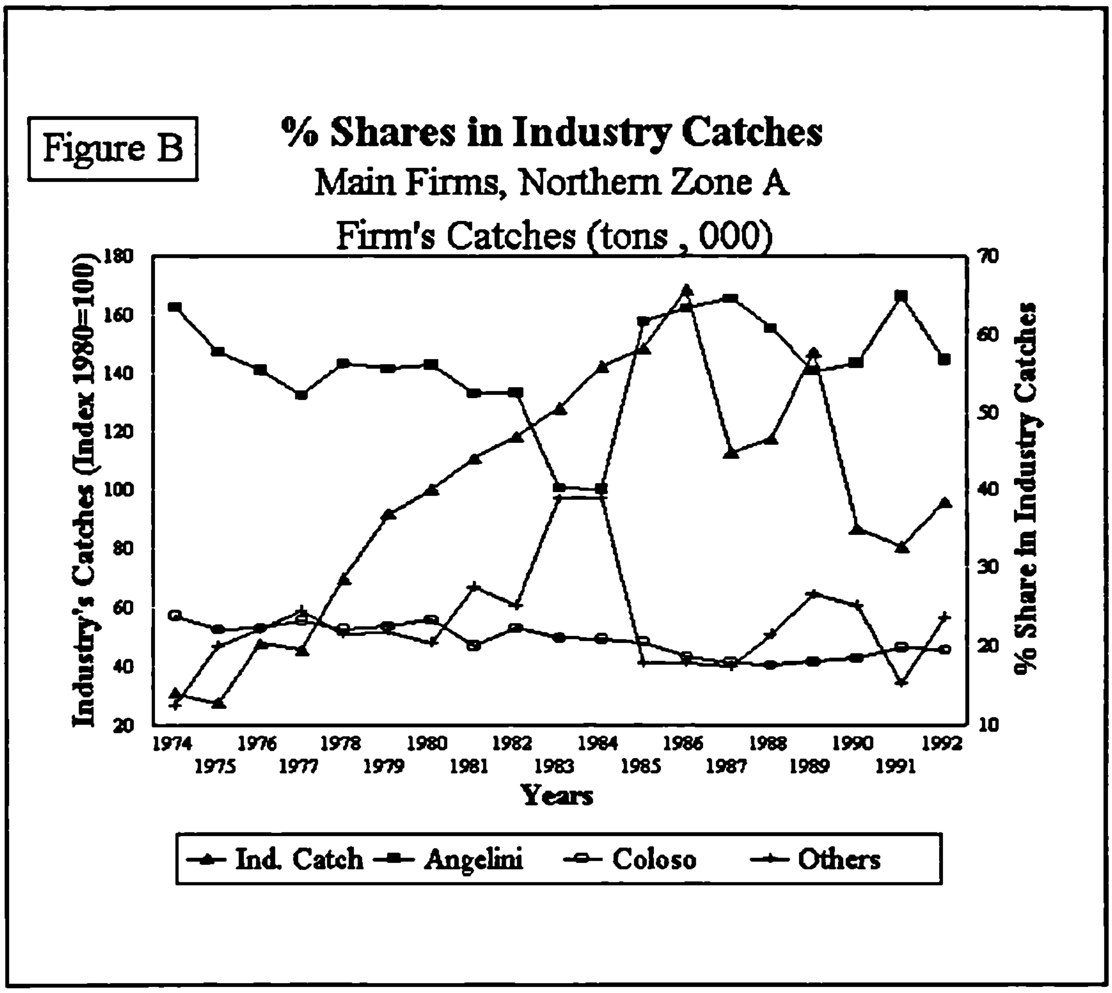




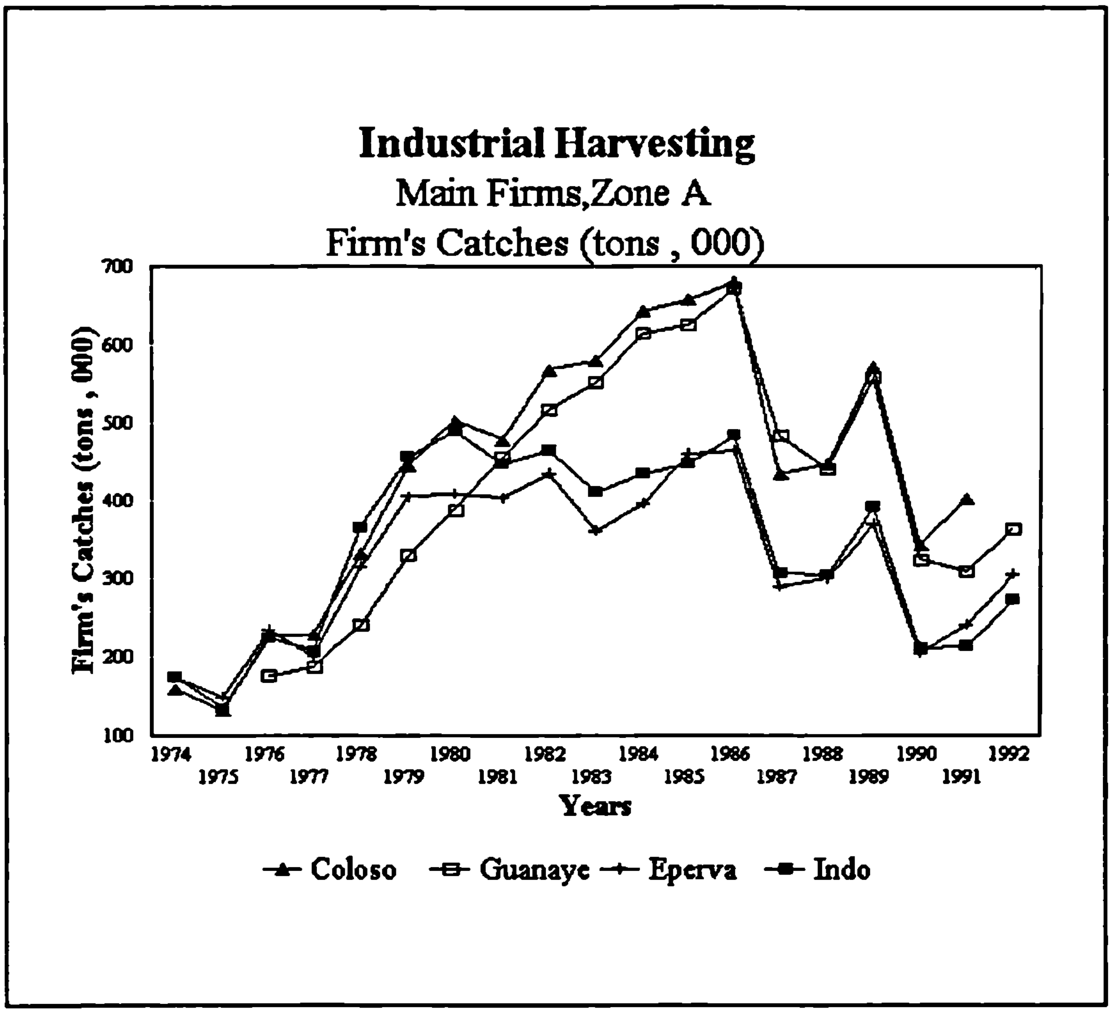
Appendix 3.2.A



Appendix 3.2.B



Appendix 3.3


Industrial Harvesting
Main Firms,Zone A
Firm's Catches (tons , 000)
Firm's Catches (tons , 000)
700
600
500
400
300
200
100
1974
1975
1976
1977
1978
1979
1980
1981
1982
1983
1984
1985
1986
1987
1988
1989
1990
1991
1992
Years
Coloso
Guanaye
Eperva
Indo

Appendix 3.4.A
TOTAL CATCHES (Tons,000)
Chilean Northern fishery (Zone A)
Industrial fleet

	Industry		Angelini (1)			Coloso SA			Other firms		
Year	Catch	Index	Catch	Index	%	Catch	Index	%	Catch	Index	%
1974	664.6	30.9	422.4	34.9	63.6	159.2	31.6	24.0	83.0	18.8	12.5
1975	592.0	27.5	342.0	28.3	57.8	131.0	26.0	22.1	119.0	26.9	20.1
1976	1027.9	47.7	570.8	47.2	55.5	229.0	45.4	22.3	228.1	51.7	22.2
1977	979.0	45.5	511.1	42.3	52.2	228.0	45.2	23.3	239.9	54.4	24.5
1978	1504.4	69.8	847.0	70.1	56.3	334.0	66.3	22.2	323.4	73.3	21.5
1979	1974.4	91.7	1099.2	90.9	55.7	445.0	88.3	22.5	430.2	97.5	21.8
1980	2154.0	100.0	1208.6	100.0	56.1	504.0	100.0	23.4	441.4	100.0	20.5
1981	2387.5	110.8	1251.1	103.5	52.4	478.0	94.8	20.0	658.4	149.1	27.6
1982	2544.1	118.1	1336.4	110.6	52.5	568.0	112.7	22.3	639.7	144.9	25.1
1983	2761.6	128.2	1108.5	91.7	40.1	580.0	115.1	21.0	1073.1	243.1	38.9
1984	3069.4	142.5	1230.5	101.8	40.1	641.6	127.3	20.9	1197.3	271.2	39.0
1985	3206.6	148.9	1976.2	163.5	61.6	657.5	130.5	20.5	572.9	129.8	17.9
1986	3640.4	169.0	2308.3	191.0	63.4	680.3	135.0	18.7	651.8	147.6	17.9
1987	2426.2	112.6	1568.7	129.8	64.7	435.0	86.3	17.9	422.5	95.7	17.4
1988	2534.4	117.7	1541.5	127.5	60.8	446.0	88.5	17.6	546.9	123.9	21.6
1989	3175.2	147.4	1757.6	145.4	55.4	572.0	113.5	18.0	845.6	191.6	26.6
1990	1866.5	86.7	1051.7	87.0	56.3	344.3	68.3	18.4	470.5	106.6	25.2
1991	1735.9	80.6	1127.1	93.3	64.9	402.2	79.8	23.2	206.6	59.9	11.9
1992	2063.6	95.8	1172.7	97.0	56.8	432.0	85.7	20.9	458.9	110.7	22.2

Notes:
(1): the *Angelini group* includes:
1974-92: Eperva, Indo, Iquique.
1974-90: also Chilemar
1984-90: also Tocopilla
1985-92: also Guanaye
1989-90: also Pta. Angamos
(2)%: indicates percentage share in industry's catches.

Sources: Own calculations based on:
(a)Financial reports from different fishing companies.
(b)Annual Fishing Statistical Report, SERNAP (National Fishing Service).

Appendix 3.4.B
THE ANGELINI GROUP
Total catches (tons,000), Index: 1980=100

Year	Chilemar catch	Chilemar Index	Guanaye catch	Guanaye Index	Eperva catch	Eperva Index	Indo catch	Indo Index	Iquique catch	Iquique Index	Tocopilla catch	Tocopilla Index	P.Angamos catch	P.Angamos Index	Angelini Group catch	Angelini Group Index
1974	33.1	23.7			175.1	43.0	174.8	35.7	39.4	23.0					422.4	34.9
1975	27.3	19.5			147.7	36.3	134.6	27.5	32.4	18.9					342.0	28.3
1976	53.3	38.2	177.0	45.6	234.0	57.4	224.1	45.7	59.4	34.7					570.8	47.2
1977	55.0	39.4	187.0	48.2	201.0	49.3	207.7	42.4	47.4	27.7					511.1	42.3
1978	66.2	47.4	241.0	62.1	316.3	77.6	366.1	74.7	98.4	57.4					847.0	70.1
1979	105.4	75.4	331.0	85.3	405.0	99.4	454.7	92.8	134.1	78.2					1099.2	90.9
1980	139.7	100.0	388.0	100.0	407.4	100.0	490.1	100.0	171.4	100.0					1208.6	100.0
1981	155.3	111.2	455.0	117.3	402.6	98.8	447.4	91 3	245.8	143.4					1251.1	103.5
1982	155.1	111.0	518.4	133 6	434.2	106.6	464.2	94.7	282.9	165.1					1336.4	110.6
1983	182.9	130.9	552.5	142.4	360.4	88.5	409.7	83.6	155.5	90.7					1108.5	91.7
1984	150.3	107.6	613.4	158.1	394.9	96.9	433.7	88.5	183.0	106.8	68.6				1230.5	101.8
1985	160.4	114.8	625.1	161.1	460.5	113.0	447.2	91.2	195.0	113.8	88.0				1976.2	163.5
1986	179.0	128.1	671.8	173.1	464.6	114.0	482.7	98.5	270.8	158.0	144.8		94.6		2308.3	191 0
1987	80 8	57.8	484.0	124.7	291.1	71.5	308.0	62.8	194.9	113.7	109.9		100.0		1568.7	129 8
1988	90.2	64.6	440.4	113.5	299.7	73.6	304.3	62.1	189.6	110.6	108.3		109.0		1541.5	127.5
1989	106.0	75.9	558.3	143.9	369.8	90.8	391.1	79.8	137.6	80.3	66.1		128.7		1757.6	145.4
1990	57.5	41.2	325.7	83.9	203.4	49.9	210.2	42.9	152.3	88.9	40.0		62.6		1051.7	87.0
1991	73.2	52.4	308.8	79.6	241.7	59.3	212.8	43.4	195.1	113.8	18.2		77.2		1127.1	93.3
1992	*	-	364.0	93.8	305.0	74.9	272.5	55.6	103.1	60.2	43.3		84.7		1172.7	97.0

Notes:
The Angelini Group includes the following firms:
1974 92: Eperva, Indo, Iquique.
1974-91: also Chilemar.
1984-92: also Tocopilla.
1985 92· also Guanaye.
1986 92: also Punta Angamos.
*: This firm has been merged with Eperva since 1992.

Sources: Own calculations based on:
(a)Financial reports from different fishing companies.
(b)Annual Fishing Statistical Report, SERNAP (National Fishing Service).

CHAPTER 4
MOTIVATION AND STRUCTURE FOR OLIGOPOLY MODELS

(4.A) Introduction

In this chapter we explain the main motivations leading us to develop the oligopoly harvesting models offered in chapters 5 and 6. We also explain some of the key assumptions of these oligopoly models.

In the following chapters we develop two basic models, one static and the other dynamic, that analyse the issue of overfishing within a multi-firm harvesting fishery subject to a common property fish stock. Each firm's harvesting decision is summarized in the choice of a single variable input that we call fishing effort. We develop these models within a deterministic oligopoly setting. Our analysis compares the relative overfishing ranking between noncooperative Cournot-Nash and Stackelberg harvesting equilibria. In our analysis noncooperative harvesting implies that externalities, originating from common property fish stocks, are not fully internalized by each firm's harvesting decision.

Section (4.B) describes the main motivations and key assumptions that lead to the models of chapters 5 and 6. Oligopoly equilibrium concepts, firms' price taking behaviour, closed entry and optimality benchmarks are some of the key assumptions which are described and justified. Section (4.C) comments on the exclusion of processing stages from our fishery models in chapters 5 and 6. This section also describes evidence (additional to the analysis in section 3.C) that suggests the presence of industrial concentration in some important marine industrial fisheries. Section (4.D) offers a final remark.

(4.B) Motivations and key assumptions.

Why are we interested in comparing noncooperative Cournot-Nash and Stackelberg harvesting equilibria? Our main motivation arises from the intent to develop a formal and consistent framework aimed at analysing the traditional and intuitive proposition that the common property of fish stocks introduces incentives to overdeplete the common pool natural resource. In this endeavour, by assumption, we preclude the possibility of cooperative harvesting strategies aimed at internalizing the externality effects brought about by the common property feature. Our main focus is on the case of common property marine industrial fisheries, where the evidence in favour of successful, in the sense of self-enforced and/or credible, cooperative harvesting agreements is very scarce indeed (for instance, see Swanson, 1992).

The reasons underlying the absence of self-enforced or credible cooperative agreements in marine industrial fisheries seem to be related to the costs of preventing free riding or defections from collective cooperative agreement in harvesting. These costs are generated by the need to monitor each firm's harvesting and to punish deviations from each individual firm's harvesting quota. We will not pursue an explicit modelling of these costs. Instead, it suffices for our purposes to suppose that these costs tend to increase with either the number of firms with access to the common pool resource, the size of the harvesting marine area, or the degree of heterogeneity across the firms' harvesting technologies (see Fisher, 1981, ch. 3; Eggertsson, 1990, ch. 4 and 8; Libecap, 1989, ch.5).

Within the context of non-cooperative harvesting outcomes, the traditional research on fisheries (for instance, Gordon, 1954; Scott, 1955 and Weitzman, 1974) has usually assumed open access conditions and decentralized multi-firm harvesting such that each harvesting firm is *assumed* to behave as an static optimizing agent. In most occasions the analysis considers decreasing harvesting returns at the aggregate or industry level use of a single variable input. By adding the open access condition to this technological feature, it is possible to derive overproduction propositions when the industry's harvesting equilibrium is compared to the optimal solution. However, none of these traditional analyses have explicitly considered strategic features in the harvesting competition for the freely available Ricardian rents of the common pool resource. By contrast, in the following two chapters we will focus our attention on comparing different types of strategic interactions among harvesting firms. In our discussion, the concept of strategic interactions is meant to imply oligopolistic harvesting games within multi-firm and deterministic common property fisheries.

Since the early 1980s an increasing number of papers have modelled the overdepletion of common pool fish stocks by resorting to the use of Nash type conjectures within multi-firm oligopoly fisheries, subject to decreasing returns on the use of a single variable input. In the following chapters we review some of these analyses, within static and dynamic frameworks. The intuitive reasoning underlying this type of analysis relates to the informal proposition that a *sufficiently large* number of firms with access to the common pool resource, such that each of these firms harvests a *sufficiently small* proportion of the total common property resource, will tend not to internalize the harvesting interdependencies across firms that arise from the commonality of fish stocks. In static models these interdependencies are usually modelled as congestion problems, even though several of these models do not offer an *explicit* modelling of the externality issue. In fact, congestion is frequently modelled as implicitly implying decreasing returns on the aggregate (industry level) use of a single variable input. In dynamic settings, externality problems are usually modelled as arising from the effect of firms' current harvesting on the future availability of the common property fish stock.

However, few efforts have been devoted to generalizing the Nash overfishing outcomes to other oligopolistic or, more generally, strategic settings. In the following chapters we review some analyses of oligopolistic harvesting games subject to non-Nash strategic conjectures. Among them, a few models that have extended their analysis to leader-follower settings or Stackelberg equilibria. Our efforts in the next two chapters are devoted to further advance on this line of research. More precisely, we will study the relative overfishing ranking between Stackelberg and Cournot-Nash harvesting games in static and dynamic contexts. We aim to analyse how different structures of harvesting incentives can change the overfishing ranking between these two equilibrium concepts. But why is the study of Stackelberg equilibria an interesting exercise with respect to the overdepletion of common pool marine resources? The answer arises from the second source of motivation that underlies our interest in comparing Cournot-Nash and Stackelberg overfishing outcomes: industrial concentration.

In chapter 3 we have described examples of marine industrial fisheries subject to the presence of industrial concentration. In section (4.C) we offer additional evidence which suggests that industrial concentration in marine industrial fisheries seems not to be such an uncommon feature. In our discussion industrial concentration loosely implies the presence of large firms, relative to the industry's size, in the harvesting sector. Hence oligopoly rather than perfectly competitive models may be appropriate.

Cournot-Nash harvesting models can accommodate competition among the few. In the following two chapters we review some fishery models that develop this line of thought. The use of Nash type conjectures is frequently justified as a reasonable approximation for fishing industries such that each firm tends to perceive its own harvesting as negligible in comparison with the industry's total catches. By this token, the assumption of rivals' insensitivity to marginal changes in individual firms' harvesting seems to be justified.

However, when we encounter fishing industries where one firm, or a group of equity and managerially related firms, controls either forty, fifty or even sixty per cent of the industry's total harvesting, the justification for rivals' insensitivity to changes in the harvesting strategy of these large firms becomes implausible. In these cases we should probably consider alternative models of strategic interactions across harvesting firms with access to the common pool resource, rather than only those defined by Nash conjectures. Our consideration of Stackelberg equilibria is justified on these grounds.

There are plenty of other possibilities to account for model refinements aimed at considering the harvesting impacts from relatively large firms. The different modelling possibilities are related to the definition attached to the concept of a *large* or *dominant* firm. For instance, and only to mention a few possibilities, we could consider dominant firms who base their dominance, or leadership, and strategic behaviour upon either (i) the access to some specific technological advantage, or (ii) their endowment with advantageous private information sets, or (iii) the possibility of exerting price setting powers in segregated markets or markets subject to some type of price discrimination. However, in our models we do not consider any of these options. We rule out any explicit modelling of (asymmetric) informational advantages, given our focus on deterministic models. The issue of technological advantages will be considered in a very simple way; that is, by introducing a scaling factor within the firms' harvesting technologies such that it will imply a productivity advantage in favour of the firm defined as the *leader*. Our models will consider price taking harvesting firms, both in output and input markets[1]. We explain this choice in the next paragraphs.

In keeping with the above, we summarize the idea of a *large* or *dominant* firm by resorting to the definition of Stackelberg leadership attributes. This implies that we will assume the existence of a leading firm, the *leader*, that is endowed with a first mover advantage over his rivals, the *followers*. The first mover advantage will consist in the leader's ability to *credibly commit* to a given harvesting strategy over a given time period. The follower firms know the leader's commitment or signalling policy. The leader also knows each follower's reaction to his signalling policy.

[1] In standard oligopoly models firms face a negative sloped industry demand curve. In this setting the strategic interaction among firms is captured by the pecuniary externalities that firms impose on each other, via the effect of individual firm outputs on the industry price. In our models with price taking firms, the source of strategic interactions stems from technological externalities, that each firm's harvesting imposes on her rivals' harvesting, arising from common property fish stocks. Despite this difference with standard oligopoly models, in our analysis we can use the same type of oligopoly modelling strategies.

Followers will behave according to Nash type conjectures, and they will not be allowed to collude as an equilibrium strategy. These features are standard conditions within Stackelberg models.

Let us turn now to three other important features that will be common to our modelling in the chapters that follow.

(4.B.1) Price taking behaviour.

Our analysis considers *price taking* harvesting firms in both input and output markets, even when we introduce the presence of a Stackelberg leading firm. Chapter 1 has already described the theoretical inquiry underlying the choice of this assumption. This assumption is also motivated by the industrial structure of the specific marine industrial fisheries that initially led to our interest in the overfishing issue: the Chilean pelagic fisheries involved in fish meal production (chapter 3).

Fish meal is a commodity mainly used to feed livestock and in some fish farming (e.g., the salmon industry). In the Chilean case, this is an almost 100 per cent export industry that essentially considers its selling prices as given. The price taking behaviour is mainly explained by a high degree of demand substitution that exists between fish meal and other substitutes such as soybean meal[2]. Consequently, hereinafter we will suppose that our models in chapters 5 and 6 consider a common pool fishery that produces a fish meal type product such that the selling price is exogenous to the industry and hence to each firm's production decision.

In the case of input markets for harvesting firms we also assume price taking behaviour. We assume there is a single variable input: *fishing effort*. We could justify this composite input in a variety of ways. The simplest is to assume that different variable inputs are used in fixed proportions (e.g., working capital, labour related

[2] This feature tends to nullify any possibility of price setting powers due to concentration on the supply side. In 1992, Chilean fish meal exports represented a third of the world total exports of this commodity. In terms of world production, Chilean fish meal production represented 19.4% of that total in 1992 (Calfucura and Jiles, 1994).

inputs, boats' fuel, operational depreciation of fishing nets, gears and other specific fishing equipments). We do not formally model fixed inputs or fixed costs. Technological indivisibilities can only be indirectly inferred from decreasing returns in the use of the variable input fishing effort. The exclusion of fixed costs is consistent with our modelling of the total number of firms with access to the common property resource as an exogenous variable.

The price taking behaviour of harvesting firms in input markets (in our models, the market for fishing efforts) seems to be a plausible assumption when we consider numerous small harvesting firms, which may be modelled as behaving according to Nash type conjectures. In the case of adding the existence of a *relatively large* harvesting firm versus the other firms, that will be modelled as a Stackelberg oligopoly equilibrium, we might wish to consider the possibility of the large firm enjoying price setting powers in input markets. However, for the sake of simplicity our modelling efforts will exclude this option. We could suppose, for instance, that fishing effort units are sufficiently mobile that they can move to other fishing grounds and/or fishing industries[3].

(4.B.2) Closed entry.

Chapters 5 and 6 consider common property fisheries subject to closed entry. We do not model the decision making mechanism that determines the closed entry solution. This implies that the total number of firms with access to the common pool resource is an exogenous variable. We do so partly motivated by the widespread increasing worldwide trend, which has prevailed since the early 1980s, to control the access to national marine fisheries (Scott, 1988; Wilen, 1988). Our case study of Chilean pelagic fisheries ratifies this trend (chapter 3).

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[3] For the case of fishermen's labour efforts, the assumption of a relatively high geographical mobility seems to be realistic. We have verified this feature, for the case of Chilean industrial pelagic fisheries, in discussions with fishing entrepreneurs who work in these fisheries (personal interviews carried out during 1993-94).

This assumption will also help us to study how increases in the number of firms with access to the common pool fish stock modify the harvesting incentives faced by different types (leader/follower; static/dynamic profit optimizer) of non-cooperative harvesting firms. For instance, this type of analysis will allow us to explore whether or not static optimizing behaviour is the limiting case of a dynamic Cournot-Nash multi firm fishery as the number of firms increases (chapter 6).

(4.B.3) Optimality benchmarks.

We follow the standard *first best* optimality yardstick used in overfishing analyses. This yardstick defines efficiency as corresponding to the harvesting decisions taken by a social planner who is institutionally costless, as well informed as private firms, and with full control over the industry's total harvesting fleet (see, for instance, Gordon,1954; Scott, 1955; Clark, 1980; Levhari and Mirman, 1980). In models with price taking behaviour, this definition is equivalent, in terms of harvesting outcomes, to the case of a profit maximizing sole owner of fish stocks. This optimality yardstick implies, by definition, a full internalization of any externality effect that may arise from the common property of fish stocks.

The oligopoly harvesting models in chapters 5 and 6 also consider second best welfare solutions to assess the inefficiencies related to overfishing. These solutions are defined by welfare optimization problems where a social planner has control only upon a limited number of harvesting firms within the common pool fishery. This type of exercise aims to illustrate arguments of *constrained* optimality, where a fishing regulator has limited control and enforcement powers upon the regulated firms' actions.

(4.C) Industrial concentration in marine industrial fisheries: additional evidence.

Section (3.C) has already described the phenomena of industrial concentration and vertical integration that we encounter in the two most important Chilean marine industrial fisheries. Table 3.6 accounts for the case of the Southern pelagic fishery, while Appendix 3.2.B plots the shares, in regional annual catches, of the main multi-firm fishing conglomerate which operates in the Northern pelagic fishery. In both fisheries, the ten biggest individual firms concentrate more than 50 per cent of the industry's total production.

Using the latter as an arbitrary yardstick for the presence of industrial concentration[4], this section describes evidence that suggests the presence of industrial concentration in two other important marine industrial fisheries: (i) the Peruvian anchovy fish meal fishery during the mid- and late-1960s and during the early 1970s, and (ii) the US tuna fishery, during the 1970s.

Before going into details, we briefly comment on the research approach that, until recently, has dominated the study of the issue of industrial concentration in industrial fisheries; that is, the harvesting effects of having processing sectors with price setting powers in the market for raw fish catches.

(4.C.1) Monopsonistic powers in the market for catches.

The more traditional research approach to the issue of industrial concentration in fisheries has consisted in exploring the effects of economies of scale in the processing stages of fishing industries. The pioneering key work was Crutchfield and

[4] This is obviously an arbitrary definition of industrial concentration. But our purpose is just to define a clear yardstick to compare with the *Concentration ratios* that we encounter in the industrial fisheries analysed. The *Concentration ratio* (CR) is one of the simplest ways to measure industrial concentration. It simply sums over the shares, usually with respect to industry output, sales or some other variable that measures scale of operation, of a given number of firms within an industry. See Waterson (1984, ch.9), Stigler (1983, ch.4), Saving (1970), Hannah and Kay (1977, chs. 2 and 4), and Scherer (1980, ch.3), for analyses and further references on this measure of concentration and other alternative indexes. Stigler (1983,p.30) mentions that the first industrial censuses (mid 1930s) considered CR for the four largest firms (in US), for the three largest (in UK), and in Canada the number of firms necessary to account for 80 per cent of industry output. More modern analyses tend to consider CR (in terms of shares of industry output) for a number of firms that varies between the largest 4 to the largest 20 firms. (Stigler, 1983, p.3, and Scherer, 1980, p.57).

Pontecorvo's (1969) book on the Pacific salmon fisheries. These authors concentrated on studying the harvesting consequences of an increasing returns to scale processing sector with monopsonistic price powers in the market for raw fish catches. Although their study have no explicit model, their key conjecture was that a fully monopsonistic processing firm, when confronting a non-colluding (competitive) multi-firm harvesting sector, could achieve a Pareto efficient harvesting of a common pool fish stock, even if processing and harvesting firms were not vertically integrated.

The basic intuitive reasoning was that the price setting powers in the hands of the monopsonistic processor would allow him to appropriate, and hence internalize, the fish stock's rents that otherwise would be dissipated by the competitive, and hence passive bargainer, harvesting sector. Therefore, an intertemporal profit-optimizing monopsonistic processor, using social discount rates, could achieve a Pareto optimal harvesting path by choosing a suitable price path for harvests. The empirical fact that many fisheries with oligopsonistic processing sectors were "manifestly not run in a socially optimal manner" (Munro, 1982b, p.188) could be ascribed, according to Crutchfield and Pontecorvo's proposition, to the fact that the oligopsonies were, contrary to appearances, weak. If this reading were right, striking policy implications could be derived. Instead of persevering with ineffective as well as inefficient restricted entry programs aimed at the harvesting sector alone[5], these conjectures could suggest that policy should be aimed at increasing the monopsony power of processors[6].

Later analyses have qualified the conditions under which these arguments can be valid. Critical analyses and additional refinements of the Crutchfield and Pontecorvo's proposition can be found in Clark and Munro (1980), who focus their analysis on the overconservation effects, in a Pareto inefficiency sense, that

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[5] On studies about these inefficiencies, see the references quoted in chapter 3.

[6] This idea was first raised in Cassidy (1973).

monopsonistic price powers bring about, when the harvesting sector faces *increasing* marginal costs as the industry's harvest rate increases. As a result of this, Clark and Munro's first best policy corresponds to full vertical integration[7]. A similar conclusion is obtained by Munro (1982b) when exploring the case of a bilateral monopoly (cooperative) bargaining game, for the fish stock's rents, between a monopsonistic processor and a monopolized (fully collusive) harvesting sector.

Schworm (1983) generalizes Clark and Munro (1980) by adding (i) a (static) congestion externality problem, and (ii) *asymmetric* convex production technologies across harvesting firms. By doing so, Schworm proves that a full monopsony in the processing stage need not lead to a first best outcome when features (i) and (ii) are present. In this case, Schworm argues that Pareto efficiency would require control over the harvest rates of each individual firm, while the monopsonist has, in general, only a single instrument, the price for harvests, which is common to all harvesting firms. Finally, Stollery (1987) explicitly introduces entry and/or exit costs within the harvesting sector and argues that this non-perfect malleability feature is a necessary condition for the validity of the over conservation effect and hence the vertical integration first best proposition stated in Clark and Munro's (1980) analysis.

Notwithstanding the potential relevance of the issue of processing fishing sectors subject to increasing returns to scale, in the following chapters we do not consider the issue of monopsonistic price powers in the market for catches. This is motivated by the sake of simplicity and modelling tractability. By doing so, we concentrate on the study of oligopolistic interactions within a (one-sector) harvesting fishery that exploits a common property fish stock. We aim to specialize our discussion on the overfishing outcomes that might be anticipated from the presence of concentration at the harvesting sector and, hence, from some plausible resulting

[7] In order to assure the validity of this first best prescription it is necessary to assume that: (1) the monopsonistic processor has a discount rate which is identical to the social rate of discount, (2) the harvesting sector is perfectly competitive and subject to increasing marginal costs of harvesting, and (3) the processor is a price taking firm in her selling market.

oligopoly harvesting equilibria. With this objective we compare overfishing results under Cournot-Nash and Stackelberg equilibria.

Let us now turn to the additional empirical evidence in favour of industrial concentration in the harvesting stage of marine industrial fisheries.

(4.C.2) The Peruvian anchovy fishery.

Between the mid 1960s and early 1970s this fishery's harvests were the largest in the world (Idyll, 1973). Anchovies were used in the production of fish meal and fish oil. It was in 1972-73 that the economic collapse of this fishery took place (see Thorp and Bertram, 1978; Clark, 1981 and Fitzgerald, 1979). The collapse happened after a prolonged period of free access and increasing industry catches that were combined, during 1972-73, with a significant negative shock from the "El Niño" marine phenomenon. Table 4.1 provides an idea of the magnitude of this collapse problem: from a maximum annual catch of 12 million tons in 1970, the annual harvest of Peruvian anchovies fell to less than 2 million tons in 1973. In the following decade (1974-84) the average annual catch was only 1.6 million tons.

Despite *de facto* open access, there is evidence of increasing industrial concentration within this industry, although only manifested as a clear trend as from 1966[8]. Some historical descriptions of this phenomenon can be found in Roemer (1970; pp.72-89), Fitzgerald (1979, p.113-114), Thorp and Bertram (1978, pp. 242-250) and Abramovich (1973). From the last two works we extract the concentration numbers that are offered in Tables 4.2 and 4.3. Table 4.2 shows that between 1966-70 the share of the 'top producers' in total fish meal production ranged from 61 to 82 per cent. We could not clarify the precise definition of 'top producers' which is used by a Peruvian annual Fishing Report. However, by using the detailed information in Abramovich (1973), for the year 1968, we calculated the corresponding shares, for different producers' ownership types, of the 10 biggest

[8] This fishery started its industrial operation in 1957 (Idyll, 1973).

firms within the Peruvian fish meal industry. Summing up, over the different ownership types, we see that in 1968 the top 10 producers controlled 51 per cent of the industry's production. This percentage leads us to deduce that the definition of 'top producers' in Table 4.2 must cover a greater set than the 'top ten'. Despite the latter ambiguity, these numbers clearly suggest an industry under some degree of industrial concentration. Most of the main producers had also vertically integrated both processing and harvesting operations (see studies above cited).

(4.C.3) The US tuna fishery.

Our key source with respect to this fishery is Gallick's (1984) study, in which the main concern is the efficiency of exclusive dealing and other vertical arrangements between processors and harvesters in the US tuna canning industry. Nonetheless, for our current purposes it suffices to quote two short paragraphs from Gallick's study:

> "...concentration at the processing level was relatively high. In 1952, for example, three major canners ... accounted for 70-75 per cent of total canned tuna production in the Southern California area. A few large processors were alleged to control domestic tuna canning *and harvesting*." (page 79; the italics is ours).

and

> "Between 1973 and 1978, four firm concentration at the processing level averaged 79 per cent with the top two processors controlling over 60 per cent of canned tuna sales. No entry at the processing stage occurred during this period despite major additions of plants and vessels by the top three processors" (page 81).

Although the numbers quoted are with respect to the concentration issue in the processing sector, the author's analysis of vertical contracting issues allows us to deduce that the concentration in processing operations was *also* relevant within the harvesting sector. In fact, Gallick's study offers diverse examples of processors' control devices over the boat owners' harvesting operations. Several of these control devices were directly related to processors' equity rights in harvesting firms. Consider, for instance, the following information from Gallick's study.

TABLE 4.1
Peruvian anchovy fishery

		(1) Annual Catches (tons, 000)	(2) Vessels (N° units)	(3) Public Sector Ownership % Share
Average	1960-64	6102.2	1178	
Average	1965-67	8532.3	1614	
Average	1968-71	10444.2	1479	
	1972	4447.2	1399	
	1973	1512.8	1256	10.4
	1974	3582.4	795	96.5
	1975	3078.8	785	97.0
	1976	3863.0	556	95.9
	1977	792.1	514	90.0
	1978	1187.0	504	87.5
	1979	1362.8	484	70.5
	1980	720.0	403	59.4
	1981	1225.1		72.3
	1982	1720.4		64.2
	1983	118.4		33.9
	1984	22.9		26.8
	1985	344.3		29.9
	1986	3481.8		36.9
	1987	1764.2		44.3
	1988	2701.1		36.0
	1989	3718.7		36.7

Sources: (1) Sueiro (1991).
(2) Agüero (1987).
(3) "Almanaque Estadístico: Perú en números 1990" (Statistical Almanac: Perú in figures for 1990), Lima, Perú.

TABLE 4.2
Peruvian anchovy fishery
Share of the main firms in total fishmeal output, 1966-70
(percentages)

	Firms in the "Top Producers" List				Producers not considered
	(1) Wholly-foreign	(2) Joint foreign-Peruvian	(3) Peruvian	(4) Total	
1966	17.4	14.5	28.9	60.8	39.2
1968	23.1	9.9	40.9	73.9	26.1
1969	24.0	10.3	47.6	81.9	18.1
1970	20.4	5.1	49.1	74.6	25.4

Notes:
Calculated from the lists of *top producers* published in *Anuario de Pesca* (Fishing Yearbook) (1965-6), p.148; *Peruvian Times*, Fisheries Number, Oct. 20, 1967, p.7; Fisheries Supplement, Mar.28, 1969, pp.20-1; Fisheries Supplement, July 24, 1970, p.57; and Fisheries Supplement, Mar.3, 1972, p.68.
The definitions used are copied from Abramovich (1973).
Source: R. Thorp, G. Bertram (1978, p.249).

TABLE 4.3
Peruvian anchovy fishery
Share of 10 biggest firms in total fishmeal output, 1968

	%	N° Firms
(1) Non-elite Peruvian Entrepreneurs	28.0	4
(2) Traditional Peruvian elite	5.7	2
(3) Wholly-foreign firms	11.7	2
(4) Joint ventures (foreign-Peruvian)	5.4	2
TOTAL	50.8	

Source: Abramovich (1973).

> "A processor entrant may find it difficult to obtain a domestic source of supply. Existing processors owned or controlled 80 per cent of the domestic fleet during the 1972-77 period. The remaining vessels, except for six, were under contract to one of the major processors" (p.85).

Despite the ambiguity related to the *specific* concentration levels involved in the harvesting sector, it seems to us that the information provided by Gallick is clear with respect to the presence of a significant concentration in harvesting operations.

(4.D) Final remark.

The empirical evidence described in sections (3.C) and 4.C) suggests the presence of industrial concentration in a series of important marine industrial fisheries. This evidence suggests that Cournot-Nash equilibria, which are more appropriate for a *large number* oligopoly case, may not be sensible for some fisheries with high industrial concentration. Therefore, there arises the need for models with more active features of strategic interaction. A hierarchical Stackelberg equilibrium is the simplest of these models. In the following two chapters we use this notion of oligopoly equilibrium as a first attempt to investigate the implications of common pool harvesting fisheries subject to industrial concentration. We study these implications by comparing overfishing results under Cournot-Nash settings and Stackelberg equilibria. In the latter case, we simplify the illustration of a fishery under industrial concentration by assuming the existence of a *single* harvesting firm endowed with Stackelberg leadership attributes.

CHAPTER 5
OVERFISHING IN A STATIC SETTING.

(5.A) Introduction.

In this chapter we explore overfishing in a static and deterministic framework. We concentrate on analysing the overfishing ranking of Cournot-Nash and Stackelberg equilibria. The Cournot-Nash setting is intended to approximate a decentralized and non-cooperative multi-firm fishery, while the Stackelberg equilibrium is meant to imply a non-cooperative fishery subject to industrial concentration, where a leading firm is a Stackelberg leader. In the timeless setting of this chapter, overfishing is modelled by building a congestion externality into the harvesting technology. The externality feature arises as a result of the commonality of fish stocks.

The timeless structure in this chapter precludes an explicit analysis of the *stock externality* effect as the source of overfishing outcomes (see Clark, 1976, ch.3). The effect that the industry's current total harvesting has on the future levels of fish stocks will be addressed in chapter 6. We have followed the strategy of starting our analysis within a timeless setting, with a view to gain a better understanding of how the introduction of time and dynamic arguments can act upon the overfishing ranking of Cournot-Nash and Stackelberg equilibria. The timeless setting of this chapter is consistent with assuming that each firm maximizes her profits in each period without considering the impact of current total harvesting on the future levels of the fish stock. By additionally imposing the condition that all the parameters in the model are time invariant, the firm's optimization problem will be the same for each time period. Therefore, we can exclude an explicit notation for time indexes and solve the model in a fully static fashion.

The analysis of Pareto inefficient overproduction propositions, given the presence of common property resources and congestion problems has a long history. Recall the classic controversy of the 1920s between Pigou (1932) and Knight (1924), with respect to traffic congestion problems. Gould (1972) is an illuminating re-evaluation of the Pigouvian proposition that the use of a free access resource, within an increasing average cost industry, will imply production levels that tend to expand beyond the socially optimal output. Gould's arguments generalize the Pigou-Knight setting for the case of a production technology with two variable factors in addition to the free access resource. Gould introduces the possibility of inefficient factor proportions as a consequence of the common property issue. Within this framework, overexploitation is no longer a necessary consequence of common property. However, both sources of inefficiencies (factor proportions and output levels) are directly related to the concept of inefficient rent dissipation that has been already mentioned in the foregoing chapters.

Within fishery models, there are also some discussions that model congestion externality effects. All of them consider a single variable factor setting. Smith (1968) and Brown (1974) are two examples within dynamic settings; however, in both papers the formal analysis concentrates on steady state conditions. Both papers consider full symmetry across harvesting firms. In the first, the total (endogenous) number of firms, which is determined by the industry's breakeven condition, negatively affects the total operational costs of each firm involved. The overfishing proposition is obtained by considering a free access resource which is exploited by multiple price taking firms, in contrast with the optimal harvest decisions taken by a fully centralized, and perfectly informed, social planner. Brown (1974) considers an identical optimality benchmark. Additionally, he considers price taking behaviour in input and output markets. His overfishing proof is obtained by considering an industry's (aggregate) production function, which is homogeneous of degree one in the variable factor and the common property resource, but subject to decreasing returns in the (aggregate) use of the variable factor. It is the latter modelling device that (implicitly) accounts for the existence of congestion effects. Overexploitation arises from the numerous private firms equating *decreasing* average revenue per unit of the variable factor to the common and constant factor price. However, in both papers no attempt is made to consider the impact of oligopolistic or, more generally, *strategic* interactions between rival harvesting firms.

Within the frame of deterministic and static settings, there exist a few papers that consider overproduction propositions in relation to oligopolistic and common pool fishing industries. They implicitly consider congestion effects by again basing their analysis on the use of an industry's *aggregate* production function subject to decreasing returns in the use of the single variable input. Identical firms and the assumption of a fish stock evenly dispersed make it possible to derive individual harvests which are proportional to the aggregate catch, where the proportion corresponds to the use of each firm's variable input relative to its aggregate use. Cornes and Sandler (1983) develop an analysis on these lines with price taking firms in output and input markets, considering Cournot-Nash and conjectural variations equilibria. Combining Cournot-Nash conjectures, price taking behaviour and decreasing aggregate harvest returns in the use of the variable input, Cornes and Sandler (1983) obtain an overfishing result. The comparative analysis between the Cournot-Nash case and a conjectural variations oligopoly fishery[1] allows the authors to derive the intuition that negative conjectures tend to intensify the Cournot-Nash overfishing problems, whereas the opposite occurs with positive conjectures.

Cornes, Mason and Sandler (1986) extend the previous analysis to the case of a Cournot-Nash common pool fishery where harvesting firms are *price making* agents. The key intuition is that the introduction of price setting powers brings a conservation incentive into each firm's harvesting decision. Therefore, a trade-off is created between underproduction effects, due to price setting powers, and

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[1] The authors consider an implicit function in order to define the conjectural variations factor. Denote firm i's variable fishing input by z_i and the rival firms' use of the variable fishing input by $z_{-i} = \Sigma_j z_j$, $j \neq i$. Hence, $[dz_{-i}/dz_i]$ is defined as corresponding to the implicit function $g(\theta, z_i)$, with θ as a parameter representing the rival firms' responsiveness to firm i's own fishing activity. Function g(.) can be positive, negative or equal to zero. The latter case corresponds to Nash conjectures.

overproduction incentives, due to the common pool feature. A balance between both sources of inefficiency allows the authors to derive an optimal number of firms with access to the common pool resource. Mason, Sandler and Cornes (1988) generalize this previous intuition for the case of a conjectural variation equilibrium.

In this chapter we extend the analysis of oligopolistic common pool fisheries, subject to a technological congestion externality, by concentrating on comparing the relative overfishing outcomes between a Cournot-Nash equilibrium and a Stackelberg equilibrium. The Stackelberg case is one of the simplest ways to model the harvesting outcomes from common pool fisheries subject to the presence of big firms (relative to the fishery's size). In chapter 4 we described some empirical evidence that justifies the relevance of analysing model refinements in this direction.

The analysis of the overfishing ranking between Cournot-Nash and Stackelberg equilibria is a contribution to the existing literature on fisheries. The cited models of Cornes, Sandler and Mason, which are the closest to the analysis in this chapter, do not consider the Stackelberg case. Additionally, the existing studies of oligopoly harvesting games have not modelled, within the firms' harvesting function, an explicit parameter for a congestion externality. In this chapter, by contrast, we develop this modelling option. This allows us to advance in the study of the influence that congestion effects have upon the magnitude of the overfishing problem under oligopolistic harvesting competition.

In our analysis we develop an explicit welfare yardstick, attempting to be clear on some key restrictive assumptions that support the validity of this exercise. We differentiate between a "first best" and "second best" welfare solution. The first best case assumes that the social planner has full control over the industry's total harvesting fleet. The planner's objective consists in maximizing the industry's total profits. In this case the planner fully internalizes the congestion externality effect. In the second best solution the social planner has the same objective function, but now he has control only over one harvesting firm. We suppose that: (i) the second best social planner has Stackelberg signalling attributes and (ii) that the fishing fleet under the social planner's control has a proportional productivity advantage with respect to the rival (follower) firms' harvesting fleet. In this context, we analyse the deviations from the first best welfare yardstick for the cases of the Stackelberg, Cournot-Nash and welfare (second best) equilibria. The extension of the analysis of the overfishing problem to an explicit second best welfare solution is an original contribution to the literature on static oligopoly harvesting games.

In this chapter we consider a small country fishery that produces a fish-meal type product such that the selling price is exogenous to the industry's production. We also assume that harvesting firms do not have price setting powers in their demand for input services. As a consequence of the exogeneity of the price variables, the oligopolistic character of our models derives exclusively from the firms' harvesting interdependency arising from the common property of fish stocks. The commonality feature is captured by an explicit congestion externality within the harvesting technology.

Given the setting of this chapter, with static optimizing firms, price taking behaviour and a non-zero congestion externality, we obtain the result that the presence of private Stackelberg leadership intensifies the magnitude of the tragedy of the commons, versus a Cournot-Nash setting. This result derives from the combination between congestion effects and the first mover advantage that a Stackelberg leader has. The first mover advantage allows the leader to preempt followers' harvesting, because by increasing his harvesting the leader increases the perceived congestion by the follower firms and hence the latter face incentives to reduce their fishing efforts.

Nonetheless, it is also true that the leader's marginal cost of harvesting preemption gets higher as he increases his harvesting because this increases congestion and hence negatively affects the leader's harvesting productivity. In other words, a higher value of the congestion parameter implies a trade off in terms of the leader's incentives to preempt followers' harvesting. On the one hand, a higher congestion parameter increases the leader's ability to preempt rivals' harvesting, because the penalty imposed on the rivals becomes higher. On the other hand, an exogenous increase in congestion reduces each firm's harvesting productivity, the leader included. The net balance between both incentive effects depends on the relative parameter values in the specific harvesting function that the analysis considers. But the key intuition underlying this trade off relates to the notion of how costly the attempts to preempt harvesting of rival firms might become (in terms of triggered overall productivity losses), particularly when exogenous factors (for example, a Nature's negative random shock) increase the congestion externality problem.

This chapter is organized as follows. Section (5.B) defines the initial and basic setting for analysis. Section (5.C) solves for a Stackelberg equilibrium. Section (5.D) develops a Cournot-Nash case. Section (5.E) solves for the first best optimality benchmark and discusses an overfishing proposition. Section (5.F) develops a second best planning solution and discusses the consequences in terms of overfishing. Section (5.G) explores the robustness of the previous analysis with regard to changes in the relative technological size of the congestion externality. Section (5.H) explores the overfishing consequences that stem from exogenous increases in the number of rival firms that operate in the common pool fishery. Section (5.I) concludes.

(5.B) The basic setting for analysis.

Let us consider a profit maximizing, multi-firm, fully deterministic, and single sector harvesting fishery that exploits a common property and single species fish stock[2]. Suppose that only non-cooperative equilibria are feasible in this multi-firm harvesting game due to the presence of a sufficiently high cost of monitoring rival firms'

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[2] We will not make explicit the variable *fish stock* in this chapter, given the timeless setting of our model. Firms, by definition, will not consider intertemporal effects in their harvesting choices.

harvesting. This high monitoring cost makes the emergence of a credible and sustainable cooperative harvesting equilibrium infeasible, because of the risk of cheating.

Assume that each firm i, with $i=1,..,N$, has only one choice variable that corresponds to the level of a single variable input denoted by $z_i \geq 0$. Call it fishing effort. Assume that z_i corresponds to a homogeneous mixed-input that includes all the relevant input choices within the harvesting technology. Suppose that the different inputs that z include are combined in fixed proportions[3]. Therefore, we can summarize all the input choices as the choice of the optimal level of z_i. Suppose that the per unit cost of this input is the same for all firms and independent of firms' harvesting decisions. Denote this constant per unit cost by $w>0$. Assume that there are no fixed costs. Therefore, firm i's total harvesting costs are equal to wz_i.

Denote firm i's harvest by $h_i \geq 0$. Suppose that the market price for one unit of harvest is the same for all firms and independent of firms' harvest decisions. Denote this common selling price by $p>0$. Accordingly, all harvesting firms behave as *price taking* agents, both for input and output markets. Suppose this fishery is subject to closed entry so that the total number of firms $N \geq 2$ is an exogenous variable. Denote the number of *rival* firms that any one firm has by $n=N-1$.

In the timeless setting of this chapter, we model the common property issue by the introduction of a congestion externality within the harvesting technology. The congestion effect introduces *rival consumption* across firms, in terms of their current harvesting. When a given firm increases her fishing effort, her rivals will perceive a reduction in their own harvesting levels for a given level of effort[4].

In order to model the congestion effect and to be able to obtain analytical solutions, let us consider the following harvesting technology for firm i:

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[3] This seems to be a reasonable assumption for marine industrial fisheries.

[4] It seems reasonable to expect that congestion effects are more likely to appear in a fishing industry, the higher the level of industry's total harvesting is relative to the fish stock level.

$$h_i = \alpha_i z_i - \beta_i z_i^2 - \gamma_i z_i z_{-i} \tag{1}$$

with $\alpha_i>0$, $\beta_i>0$ and $\gamma_i\geq 0$, all of them parameters; with $h_i\geq 0$ denoting firm i's harvest level, $z_i\geq 0$ her fishing effort, and where $z_{-i}\geq 0$ denotes the total fishing effort of i's rival firms; that is, $z_{-i} = \Sigma_j z_j$, $j=1,..,n$ with $j\neq i$. Parameter $\beta>0$ implies decreasing marginal product in the own effort z_i. The parameter γ introduces the possibility of congestion effects[5]. As we will see later, we need to make further assumptions about the values of the parameters in (1) to ensure sensible solutions for this model.

The harvesting function in (1) assumes that the congestion effect for each firm is proportional to her level of fishing effort. This implies that increases in other firms' fishing efforts not only reduce firm i's total catch, but *also* her marginal product of fishing effort. The latter effect seems plausible, and if it were valid we should rule out harvesting technologies such as $h_i= \alpha_i z_i-\beta_i z_i^2-\gamma_i(z_i+z_{-i})$, because in this case $(\partial h_i/\partial z_i)$ is independent of z_{-i}. In our study of Stackelberg and Cournot-Nash equilibria we will assume that $(\partial h_i/\partial z_i)$ is negatively affected by increases in z_{-i}, so equation (1) is a possible technology[6].

When we consider the case of a Stackelberg equilibrium, we want to analyse the harvesting effects that result from a Stackelberg leader that also has a productivity advantage over his followers. In order to do so, we will assume full symmetry among

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[5] We could think that α,β,γ are functions of the fish stock level, denoting it by x, presumably with $\alpha_x(x)>0$, $\beta_x(x)<0$ and $\gamma_x(x)<0$. In fact, equation (1) can be thought as a modified *Schaefer function*. This corresponds to the *linear* harvesting function (in z_i and x) that is frequently used in fishery models, with $\beta=\gamma=0$ and α_x positive but constant (see Clark, 1985, p.12). However, we will not make explicit the possibility that h_i be a function of x, because in our fully static optimizing setting x has a parametric interpretation; that is, firms do not consider the impact of their current harvesting on the future levels of x. Hence, let us retain α, β and γ as simple parameters.

[6] If we rule out the possibility that $(\partial h_i/\partial z_i)$ be affected by z_{-i}, we could consider a simpler specification of the congestion externality; for example, with a technology such as $h_i=z_i[\alpha_i-\beta_i z_i]-\gamma_i z_{-i}$.

follower firms, with the representative follower firm having a harvesting technology such that:

$$\begin{aligned} \alpha_f &= d\alpha_L = d\alpha \\ \beta_f &= d\beta_L = d\beta \\ \gamma_f &= d\gamma_L = d\gamma \end{aligned} \tag{2}$$

where $0<d\leq 1$ is a parameter that denotes a proportional productivity differential between the representative follower firm f and the Stackelberg leader that is denoted by L. We model this differential in favour of the leading firm. To simplify notation, as from here we denote the leader's harvesting parameters simply by α, β and γ.

The optimization problem for each firm i is:

$$Max_{z_i}\ V_i = ph_i(z_i,z_{-i}) - wz_i \tag{3}$$

subject to (1) and $z_i \geq 0$.

Additionally, we will suppose that the harvesting function $h_i(z_i,z_{-i}(z_i))$ is strictly concave in z_i, that is the first derivative $h_{i1}=dh_i/dz_i>0$ and the second derivative $h_{i11}=d^2h_i/dz_i^2<0$; where we are allowing for the possibility that the rivals' effort z_{-i} be a function of z_i. Denote the conjecture that firm i makes with respect to her rivals' reaction function, to marginal changes in z_i, by $\theta_i=(\partial z_{-i}/\partial z_i)$. The strict concavity of the function $h_i(z_i,z_{-i}(z_i))$ in z_i makes it necessary that $\beta_i+\gamma_i\theta_i>0$[7]. If $\theta_i \geq 0$, a case including the option of Nash conjectures, the concavity condition is valid for any feasible value of β_i and γ_i. Otherwise, the strict concavity condition calls for $(\beta_i/\gamma_i)>|\theta_i|$.

In our model, this concavity condition is sufficient to ensure the existence and uniqueness of a maximum value for function $V_i(z_i,z_{-i})$. If $\theta_i<0$, note that the strict concavity condition imposes a constraint on the relative values of β_i and γ_i which allow for sensible solutions within this model for z_i. That is, if we are going to

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[7] To be precise, this result requires us to assume that $(\partial\theta_i/\partial z_i)=0$. The specific functions of our model fulfil this condition.

characterize a maximum solution for problem (3), the parametric relative values should imply an endogenous solution for $|\theta_i|$, when $\theta_i<0$, such that $(\beta_i/\gamma_i)>|\theta_i|$. Otherwise, we will not be describing a maximum positive solution. This should be understood as imposing limitations on the robustness of our analysis.

Notation summary.

z_i	firm i's fishing effort.
z_{-i}	total fishing effort of i's rival firms = $\Sigma_j z_j$, $j=1,..,n$ with $j\neq i$.
p	selling price for harvest output.
w	per unit cost of fishing effort.
h_i	firm i's harvest level.
N	total (exogenous) number of firms.
n	Number of rival firms, n= N-1
α	linear harvesting productivity parameter.
β	decreasing return parameter for fishing effort.
γ	congestion effect parameter
d	parameter that denotes a proportional productivity differential in favour of a Stackelberg leader versus the set of symmetric followers.
f	representative follower firm in an Stackelberg equilibrium.
L	Stackelberg leader.
k	(γ/β)
V_i	firm i's profit function.
θ_i	firm i's conjecture on rival firms's reaction function with respect to marginal changes in z_i.

(5.C) Stackelberg equilibrium.

Suppose that in an N-firms fishery there exists a leading firm, call it the *leader* and denote it by L, in the Stackelberg sense. That is, the leader has a first-mover advantage over the remaining n firms, call them *followers*, in the sense that L has the ability to *credibly commit* itself to a given fishing effort strategy z_L. L's effort strategy is a signal that is observed by the followers; L also knows the followers' reaction function to z_L. For the sake of simplicity, let us assume that all follower firms are identical. Denote the representative follower firm by f, with f=1,..,n. Suppose that followers cannot sign *binding* collusive agreements among themselves. As is usual in hierarchical Stackelberg equilibria, assume that each firm f has Cournot-Nash type conjectures with respect to her rivals' effort decisions such that:

$$\frac{\partial z_{-f}}{\partial z_f} = \frac{\partial z_L}{\partial z_f} + \sum_{i \neq f,L} \left[\frac{\partial z_i}{\partial z_f}\right] = 0 \tag{4}$$

with each individual partial derivative in (4) being equal to zero.

The representative firm f's choice problem is (using (1),(2) and (3)):

$$Max_{z_f}\ V_f = pd(\alpha z_f - \beta z_f^2 - \gamma z_f z_{-f}) - wz_f \tag{5}$$

subject to $z_f \geq 0$.

Given our assumption about the strict concavity of $h_i(z_i,.)$ in z_i, the first order condition $\partial V_f/\partial z_f = 0$ suffices to characterize the unique solution to problem (5); this first order condition implies:

$$pd\left[\alpha - 2\beta z_f - \gamma\left[z_{-f} + z_f\left(\frac{\partial z_{-f}}{\partial z_f}\right)\right]\right] = w \tag{6}$$

Using the assumptions of Cournot-Nash conjectures (equation (4)) and full symmetry among followers (the latter implying that $z_{-f}=z_L+(n-1)z_f$), we obtain the following equilibrium value of z_f conditional to the observed signal z_L:

$$z_f^* = \frac{\alpha - (w/pd) - \gamma z_L}{2\beta + \gamma(n-1)} \quad , \; with \quad f=1,\dots,n \tag{7}$$

The leader knows (7), so he uses this information in his optimization problem which maximizes (3) subject to (1), (2) and (7). Given (7) and the condition of full symmetry among firms f, the leader's conjecture $\theta^L=(\partial z_{-L}/\partial z_L)$, with $z_{-L}=nz_f$, is:

$$\theta^L = \frac{\partial z_{-L}}{\partial z_L} = -\frac{n\gamma}{2\beta+\gamma(n-1)} \leq 0 \tag{8}$$

Conjecture (8) shows the *first-mover advantage* that arises from the Stackelberg leadership: as long as $\gamma>0$, the leader knows that his commitment (signalling) ability allows him to reduce his rivals' efforts by increasing his own fishing effort. In this common pool fishery, this implies that the leader can *preempt* followers' harvesting by increasing his own effort. Given that the leader is able to obtain positive profits from the marginal unit of fishing effort z_L, note that a higher value of $|\theta^L|$ will tend to increase, *ceteris paribus*, the optimal level of the leader's fishing effort. We call this phenomenon a harvesting preemption incentive for the Stackelberg leader. Notice that, *ceteris paribus*, $|\theta^L|$ increases with γ, decreases with β and $\partial|\theta^L|/\partial n>(<)0$ if $(2\beta-\gamma)>(<)0$.

The latter inequality condition summarizes the net balance between two opposite effects, upon $|\theta^L|$, that arise from changes in the number of follower firms. First, a higher n increases the aggregate preemption effect that arises from each follower firm facing the effect $(\partial z_f^*/\partial z_L)<0$ when $\gamma>0$. Second, a higher n also implies bigger congestion problems for each harvesting firm. The increasing congestion reduces each firm's catch productivity and hence each firm f's optimal fishing effort. Given this, the preemptive power of the leader, in terms of each individual firm type f, loses effectiveness as n increases, or $\{\partial|\partial z_f^*(n,.)/\partial z_L|/\partial n\}<0$[8]. This reasoning helps us to deduce that, when $(2\beta-\gamma)>0$, the changes in the (second) congestion effect are dominated by the former (aggregate) preemption effect so that an increase in n finally increases the absolute value $|\theta^L|$.[9]

In order to solve the leader's problem we consider the first order condition $\partial V_L/\partial z_L=0$, that is:

$$p\left[\alpha - 2\beta z_L - \gamma\left[z_{-L} + z_L\frac{\partial z_{-L}}{\partial z_L}\right]\right] = w \tag{9}$$

By using the symmetry condition among follower firms, so that $z_{-L}= nz_f$, and by introducing the information of (7) and (8) into (9), we obtain the leader's optimal effort:

$$z_L^*(k,d) = \frac{1}{2\beta}\left[1+\frac{kn(1-k)}{2-k}\right]^{-1}\left[\alpha - \frac{w}{p}\left[1+\frac{kn(d-1)}{d(2-k)}\right]\right] \tag{10}$$

with $k= (\gamma/\beta)$. Notice that we can interpret an increase in k as an increase in the relative technological size of the congestion effect.

Two important comments on the validity of this solution. First, note that $z_L^*\geq 0$ implies restrictions on the parameters of this model. For instance, notice that the denominator in equation (10) is positive if $k\leq 1$ or $k>2$. In these cases, the sign

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[8] In other words, the larger the industry size (in the sense of a bigger number of firms), the smaller is the leader's preemption effect on each individual follower firm.

[9] $[\partial|\theta^L|/\partial n]$ is equivalent to the following expression:

$$\left[\frac{2\beta}{\gamma} + n - 1\right]^{-2}\left[\frac{2\beta}{\gamma} - 1\right]$$

Notice that the sign of $[\partial|\theta^L|/\partial n]$ only depends on the sign of the second expression between brackets which corresponds to the condition $[2\beta-\gamma]$ (>)(<)0. A higher positive value of $(2\beta-\gamma)$ can be interpreted as a smaller size of the congestion externality, relative to the value of β (the decreasing return parameter for fishing effort).

of z_L^* depends on the sign of the expression in the numerator. For example, if $d=1$ (the Stackelberg leader has no productivity advantages over the follower firms), $z_L^*>0$ requires that $[\alpha - (w/p)]/(2\beta)>0$.

Second, in order that equation (10) represents the unique optimal solution for the maximization of the leader's profits V_L, and given that equation (8) implies that $\theta_L<0$ for $\gamma>0$, the strict concavity condition $(\beta/\gamma)>|\theta_L|$ must be fulfilled. Given the result in equation (8), this implies a parametric restriction such that $(2-k)>nk(k-1)$. Notice that there are combinations of values (n,k) for which this condition is not fulfilled.

For instance, given that invariably $n\geq 1$, if $0\leq k\leq 1$, the latter condition is always fulfilled. Accordingly, within this range of values for k we ensure the validity of solution (10) and the corresponding economic propositions that we can derive from it. If $k\geq 1.5$, however, the strict concavity condition is violated. In this case we cannot guarantee that equation (10) represents the unique maximum solution to the leading firm's optimization problem. Accordingly, the economic conclusions that we might want to derive from this result are not valid any longer. Finally, for parametric values such that $1<k<1.5$ the validity of the strict concavity condition depends on the value of n. As n increases, the range of k values that fulfils this condition becomes smaller.

Assuming that the strict concavity condition is fulfilled in solution (10), we can introduce (10) into (7) in order to obtain the optimal effort for the representative follower firm:

$$z_f^*(k,d) = \frac{1}{2\beta}\left[1+\frac{kn(1-k)}{2-k}\right]^{-1}\left[\alpha(1-Akn)-\frac{w}{pd}[1-A((2-k)(d-1)+dkn)]\right] \tag{11}$$

with

$$A = \frac{k}{(2-k)(2+k(n-1))} \tag{12}$$

Given that the representative follower firm has Cournot-Nash conjectures, we know that the sufficient condition for the strict concavity of her optimization problem in (5), that is $(\beta/\gamma) > \theta_f = [\partial z_{-f}/\partial z_f]$, is always fulfilled for β and γ greater than zero. Hence, equations (11-12) represent the unique optimal solution for the representative follower firm's optimization problem.

However, the condition $z_f^* > 0$ implies additional restrictions on the parameters of our model. To illustrate, suppose for instance that d=1. In this case, we can write (11) as:

$$z_f^*(k,n) = z_L^* \left[1 - \frac{k^2 n}{(2-k)(2+k(n-1))}\right] \tag{13}$$

with z_L^* also defined for d=1. Suppose that $z_L^* > 0$ and $k \leq 1$ in order to be sure that the solution in equation (10) represents a maximum positive solution. In this case, $z_f^* > 0$ requires that the expression between brackets in (13) be also positive. It can be easily checked that, for $k \leq 1$, if n increases then the range of k values that allows for sensible solutions for z_f^* becomes smaller.

Solutions (10) and (11-12) are complicated expressions. In order to develop some intuitions, we write these solutions as functions of parameters k and d and we specialize our discussion as follows. First, in order to compare the Stackelberg and the Cournot-Nash equilibria we will first consider a particular value of k (k=1), leaving d as a free parameter. The condition of k=1 represents a constraint on the harvesting technology $h_i(z_i, z_{-i})$. This constraint equates the level of parameter $\beta > 0$, that introduces decreasing returns in the use of z_i, with the parameter $\gamma > 0$ that introduces the congestion effect that results from additional units of rivals' fishing efforts. In other words, in this stage we are going to fix the relative technological size of the congestion externality effect. In this specific setting we will analyse how the introduction of Stackelberg leadership attributes affects the industry's fishing effort equilibrium and the magnitude of the overfishing incentives.

Second, we will study how oligopoly equilibria are affected by variations in k; that is, how harvesting incentives change, under different definitions of oligopoly equilibrium, as the relative technological size of the congestion problem varies. For the sake of simplicity, we will consider the case of a duopoly fishery such that d=1 (section 5.G).

Using the technological assumption that k=1, we can summarize the Stackelberg equilibrium as follows (using (10) and (11-12)):

TABLE 5.1: STACKELBERG EQUILIBRIUM (k=1)

(14) z_L^*	$\frac{1}{2\beta}\left[\alpha - \frac{w}{p}\left(1+n\left(1-1/d\right)\right)\right]$
(15) z_f^*	$\frac{1}{2\beta}\left[\frac{\alpha}{n+1} - \frac{w}{pd}\left[\frac{1}{n+1}+1-d\right]\right]$
Stackelberg total effort= z^S (16) $z^S = z_L^* + nz_f^*$	$\frac{1}{2\beta}\left[\alpha(1+\frac{n}{n+1}) - \frac{w}{p}\left[1+\frac{n}{(n+1)d}\right]\right]$

As expected, the leader's optimal effort increases, the higher his productivity advantage is (d falls). In our model this effect results from the reduction in congestion problems that the leading firm faces due to the lower harvesting productivity of the follower firms. In fact, a fall in d implies a lower optimal z_f^* (equation 15); hence follower firms will reduce their catch levels.

However, in the aggregate (industry level) a fall in d will imply a lower equilibrium value for total fishing effort z^S (equation 16). This means that, when k=1, the direct lower productivity effect upon followers' optimal fishing effort dominates (in the industry level) the smaller congestion externality effect that the leading firm faces and from which the latter has incentives to increase her own fishing effort. The magnitude of the marginal effect $[\partial z^S/\partial d]>0$ gets bigger with increases in the number of follower firms n[10].

Consider the case when d=1. In this case we obtain $z_L^* = [1/(2\beta)][\alpha-(w/p)]$ and $z_f^* = z_L^*[1/(n+1)]$. The aggregate (industry) fishing effort z^S is given by $[(2n+1)/(n+1)]z_L^*$. If we consider the duopoly case (n=1), we obtain the standard duopoly Stackelberg solution for homogeneous outputs such that $z_f^* = [z_L^*/2]$[11]. We can see that the productivity and price/cost parameters have the conventional effects upon optimal input choices. Increases in harvesting productivity (increases in the ratio α/β) imply higher z_L^* and z_f^*. Similarly, increases in the selling price p per unit of harvest, or reductions in the per unit marginal cost w of fishing efforts, also imply higher optimal levels for z_L and z_f.

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[10] In fact, $[\partial z^S/\partial d]$ is equivalent to:

$$\frac{1}{2\beta}\frac{w}{p}\left[\frac{1}{1+(1/n)}\right]\frac{1}{d^2}$$

[11] In the standard (textbook) duopoly Stackelberg model, firms' interactions are modelled through the use of an inverse demand function which is negatively related, in a linear fashion, to the rival firm's output. For instance, Gravelle and Rees (1992, ch. 12) consider a duopoly case with constant marginal costs of production and an inverse demand function as $p_i = a_i - b_i q_i - c q_j$, with $i \neq j$ denoting the duopolists, and c>0. For the case of homogeneous outputs (with identical marginal costs for firm i and j; and also $a_i = a_j = a$, and $b_i = b_j = b = c$), the authors obtain a Stackelberg equilibrium such that $q_i = (q_j/2)$, with firm j representing the Stackelberg leader and firm i the follower.

Let us now consider the marginal effects upon fishing effort decisions that arise in the current setting (k=1) from increases in the number (n) of follower firms. The marginal effect upon the leader's optimal effort is given by (see equation 14):

$$\frac{\partial z_L}{\partial n} = -\frac{1}{2\beta}\frac{w}{p}\left[1-\frac{1}{d}\right] \tag{17}$$

Given that $d \leq 1$, we know that $[\partial z_L/\partial n] \geq 0$. Why do we obtain this result, despite the fact that a higher n implies bigger direct congestion problems?

First, consider the case when $d<1$. Recall that the leader's strategic conjecture $\theta^L=[\partial z_{-L}/\partial z_L]<0$ increases in absolute value when n increases and $(2\beta-\gamma)>0$. This is the case when k=1. We have already deduced that in this case the relative technological size of the congestion externality (the ratio γ/β) is not high enough to overcome (in terms of bigger congestion problems as n increases) the higher *aggregate* harvesting preemption power that the leading firm has with respect to follower firms, given that a higher n amplifies the individual preemption effect $(\partial z_f^*/\partial z_L)<0$. When $d=1$, however, equation (17) tell us that z_L^* becomes insensitive to changes in n. Why does this occur?

In the latter case we obtain that the marginal harvesting productivity of the leader's fishing effort, that is $[\partial h_L/\partial z_L]$, becomes insensitive to changes in n. This occurs because the increase in the aggregate congestion effect (that result from a higher n), and the corresponding reduction in the leader's harvesting productivity, is fully counteracted by the opposite productivity effect that arises from the leader's higher aggregate harvesting preemption over follower firms (a higher value for $|\theta^L|$). In fact, $[\partial h_L/\partial z_L]$ can be written as (when $\beta=\gamma$): $\alpha-2\beta z_L- n\beta[z_f -\{z_L/(n+1)\}]$. The first element of the expression between square brackets represents the direct congestion effect that results from more numerous follower firms with $z_f>0$. The second element within the square brackets represents the higher marginal harvesting preemption that the leader can obtain if n increases and $(2\beta-\gamma)>0$. In the current case ($k=1$, $d=1$), both effects are equivalent in absolute value, because we know that in the Stackelberg equilibrium $z_f = [z_L/(n+1)]$.

In the case of the representative follower firm the analysis is simpler, because this type of firm has no harvesting preemption abilities. We know that (see equation 15):

$$\frac{\partial z_f}{\partial n} = -\frac{1}{2\beta}\frac{1}{(n+1)^2}\left[\alpha - \frac{w}{pd}\right] \tag{18}$$

In this case, as long as $[\alpha - w/(pd)] > 0$, we obtain $[\partial z_f/\partial n] < 0$. The former positive condition relates to the need of a positive marginal profit income for initial increases in the follower firm's fishing effort, that is $[\partial V_f/\partial z_f] > 0$ when $z_f \to 0$ and $z_{-f} \to 0$, in order to obtain a positive solution for the representative z_f. Given this condition, $[\partial z_f/\partial n] < 0$ is a result of the higher congestion problems that marginal increases in n produce upon each follower firm's harvesting productivity.

In terms of the aggregate fishing effort effects that result from marginal exogenous changes in n, we obtain that:

$$\frac{\partial z^S}{\partial n} = \frac{1}{2\beta}\left[\alpha - \frac{w}{pd}\right]\frac{1}{(n+1)^2} \tag{19}$$

Therefore, as long as $[\alpha - w/(pd)] > 0$ and hence $z_f^* > 0$, when $k=1$ a marginal (exogenous) increase in the number of follower firms will *invariably* imply a higher equilibrium level for the Stackelberg total fishing effort. In this case, the marginal reduction in each follower firm's optimal fishing effort (that is, $[\partial z_f^*/\partial n] < 0$) produces a smaller aggregate effect, in absolute value, than the increasing fishing effort levels that result from (i) more numerous follower firms with $z_f > 0$, and from (ii) the increasing aggregate harvesting preemption ability of the leading firm as n increases (given that $[2\beta - \gamma] > 0$, and hence $[\partial|\theta^L|/\partial n] > 0$, when $k=1$).

Let us now consider a Cournot-Nash non-cooperative equilibrium.

(5.D) Cournot-Nash equilibrium.

Imagine now that L no longer has the Stackelberg commitment attribute. Suppose that $d \leq 1$ is the only possible source of asymmetry between this firm and the n (identical) remaining firms f. Assume, hence, that all N firms behave in a Cournot-Nash fashion. Therefore, in this section notation L will only represent a firm with the possibility of higher harvesting productivity versus the representative firm f, with $f=1,..,n$.

Solving the same generic problem for each firm i (maximize (3) subject to (1) and (2)), and using the assumptions of (A.1) full symmetry across firms f, (A.2) Cournot-Nash conjectures for *all* the N firms, and (A.3) the technological assumption that $k=1$, we find the following equilibrium fishing efforts:

TABLE 5.2: COURNOT-NASH EQUILIBRIUM (k=1)

(20) z_L^*	$\frac{2}{n+2}\frac{1}{2\beta}\left[\alpha-\frac{w}{p}\left(1+n\left(1-1/d\right)\right)\right]$
(21) z_f^*	$\frac{2(n+1)}{n+2}\frac{1}{2\beta}\left[\frac{\alpha}{n+1}-\frac{w}{pd}\left[\frac{1+(1-d)}{n+1}\right]\right]$
Cournot-Nash Total Effort= z^N (22) $z^N = z_L^* + nz_f^*$	$\frac{1}{2\beta}\left[\frac{2\ (n+1)}{n+2}\alpha-\frac{w}{p}\frac{2\ (n+d)}{d\ (n+2)}\right]$

It is evident from comparing results in Tables 5.1 and 5.2 that z_L^* increases with the Stackelberg commitment ability. This is a direct consequence of the harvesting preemptive ability that the Stackelberg leader has, given his first mover or signalling ability. Directly related to this result, we can easily check that the representative z_f^* decreases when we allow the presence of a Stackelberg leader. In terms of the industry's total efforts:

Proposition 1:

In the static optimizing setting of this model, under the technological assumption that $k=1$, the introduction of a leading firm with Stackelberg commitment abilities invariably increases the equilibrium level of the industry's total fishing efforts versus the case of a Cournot-Nash setting, for the feasible values of the parameters such that z_i^*, $\forall i$, is a unique and positive variable.

Proof:

For $d=1$, $z^S = z^N + B(1/2\beta)[\alpha-(w/p)]$, with $B=[(n+2)(1+(1/n))]>0$. Also $(1/2\beta)[\alpha-(w/p)]>0$ is a necessary condition to obtain $z_i^*>0$. Therefore, if $n>0$ and $z_i^*>0$ then invariably $z^S> z^N$.

For $0<d<1$ we omit the formal proof here because it is long (see Appendix 5.1). But the idea is to express solution z^S (Table 5.1) with similar coefficients for α and (w/pd) as those in solution z^N (Table 5.2). Then, in the Stackelberg solution, we obtain a lower coefficient for (w/pd) than in z^N, an identical coefficient for α, and a proportion $[(n+2)/(n+1)][(2n+1)/2(n+1)]>1$ that multiplies the outside factor $(1/2\beta)$. Accordingly, invariably $z^S> z^N$ ■.

The result in Proposition 1 is consistent with the usual ordinal ranking of industry equilibrium outputs that results from comparing one-shot Cournot-Nash versus Stackelberg (quantity) leadership oligopoly models, when firms face interdependencies that arise from an inverse demand function that depends negatively on the industry's total output, and there are no technological externality effects as those prevailing in our current model[12]. Given this modelling setting, each firm's profit is a decreasing function of the rival firms' output. In this case, rival firms' productions behave as substitute outputs. For the case of quantity oligopoly games, the previous setting generates downward sloping reaction functions in terms of each firm's optimal output decision as a function of the rival firms' production.

The same effect of substitute[13] productions is obtained in the current oligopoly setting with price taking firms, because of the *rival consumption* effect that is introduced by the congestion parameter within each firm's harvesting function. Therefore, the consistency between our industry's fishing effort ranking (between Cournot-Nash and Stackelberg leadership equilibria) and the previous standard results in the one-shot oligopoly literature is not surprising.

We can also verify (see z^N in Table 5.2) that decreases in d imply, as in the Stackelberg case, a lower equilibrium value for the industry's total fishing efforts in the fully Cournot-Nash fishery. However, as d falls the total fishing efforts in the Stackelberg equilibrium will fall less than z^N. In fact, we can state:

Proposition 2:

In the setting of our model, and given $k=1$, decreases in the harvesting productivity "d" of the representative follower firm will invariably imply a higher positive difference between the Stackelberg equilibrium total fishing effort z^S and the corresponding Cournot-Nash total effort z^N. In other words, $(\partial\Delta/\partial d)<0$ with $\Delta= z^S - z^N$.

Proof:

Let $m_S= (\partial z^S/\partial d)$ and $m_N=(\partial z^N/\partial d)$. We know that both are positive (see Tables 5.1 and5.2). $m_S=(1/2\beta)(w/p)(1/d^2)[n/(n+1)]$, whereas $m_N=(1/2\beta)(w/p)(1/d^2)[2n/(n+2)]$

[12] See, for instance, Gravelle and Rees (1992, ch.12).

[13] Suppose a duopoly industry where firms i and j compete in quantities q_i and q_j. Denote firm i's profit function by $\Pi_i=\Pi(q_i,q_j)$. *Substitute* outputs mean that Π_i is a decreasing function of q_j and $\Pi_j(q_i,q_j)$ is a decreasing function of q_i.

And $[1/(n+1)] < [2/(n+2)]$, $\forall\, n \geq 1$. Therefore $m_S < m_N$ and hence Proposition 2 is proved ■.

What explains the result in proposition 2? This is related to the harvesting preemption ability of the *first mover* Stackelberg leading firm. Given the presence of Stackelberg commitment attributes, a leading firm that increases her productivity advantage, relative to her rivals (d falls), will have higher preemption powers to anticipate rival harvesting of follower firms. The same improvement in the relative harvesting productivity of a leading firm that does not have the Stackelberg leadership attribute will result in lower increments for her total equilibrium fishing effort.

When d falls the sequence of events is as follows. First, each representative follower firm's optimal effort z_f^* decreases. This effect is amplified n times by the existing number of type f firms. This reduces the congestion externality for each firm in the fishery. The lower congestion increases, *ceteris paribus*, the marginal productivity of each firm's fishing effort and hence each firm faces a secondary marginal incentive to increase her fishing effort. For a leading firm with Stackelberg leadership attributes the positive effect on her effort productivity implies that she can preempt more harvesting of follower firms; hence, the latter effect leads the Stackelberg leader to a greater marginal increase in his fishing effort, versus the case when the more productive firm L has no Stackelberg signalling abilities. This is the reason why with the Stackelberg leading firm the industry total fishing effort z^S falls less, when d decreases, than the fall in z^N.

Let us now consider the effects of changes in the number of rival firms on the equilibrium fishing efforts in this Cournot-Nash fishery. Let us simplify the analysis by considering the case when $d=1$. Note that in this case firms L and f correspond to symmetric Cournot-Nash decision makers. Table 5.3 summarizes the results in comparative terms with respect to the Stackelberg fishery.

TABLE 5.3: Fishing effort effects from changes in n (k=1, d=1)

Effort effects	Stackelberg	Cournot-Nash
$\partial z_L^*/\partial n$	0	$-\frac{1}{\beta(n+2)^2}\left[\alpha-\frac{w}{p}\right]<0$
$\partial z_f^*/\partial n$	$-\frac{1}{2\beta(n+1)^2}\left[\alpha-\frac{w}{p}\right]<0$	idem above
$\partial z^{industry}/\partial n$	$\frac{1}{2\beta(n+1)^2}\left[\alpha-\frac{w}{p}\right]>0$	$\frac{1}{\beta(n+2)^2}\left[\alpha-\frac{w}{p}\right]>0$

The signs of the previous expressions are derived from the fact that $[\alpha-(w/p)]>0$ so that harvesting firms be active ($z_i^*>0$). As firm L loses her Stackelberg signalling attributes, she reacts to increases in the number of rival firms as any other Cournot-Nash firm. Because an increase in n implies a higher congestion externality, each Cournot-Nash firm will always marginally reduce her fishing effort. However, given the technological assumptions such that d=k=1, the aggregate fishing effort $z^N=(z_L+nz_f)$ will increase as more firms enter into this restricted entry fishery[14].

[14] A higher value of k, that is a higher relative technological size of the congestion effect, would surely reduce the magnitude of the positive change in z^N as a result of a higher n, because in this case the resulting higher congestion problem would impose more severe marginal productivity penalties on each harvesting firm. Hence, each firm's optimal fishing effort would be lower.

Given the technological assumptions in Table 5.3, it can be easily checked that (i) $[\partial z^N/\partial n] > [\partial z^S/\partial n]$, despite that (ii) $|\partial z_f^*/\partial n|$ is greater in the Cournot-Nash case than in the Stackelberg fishery, with (i) and (ii) being valid for $n \geq 2$. It is not clear how or whether these results generalize to less specific modelling settings[15].

In the current specific setting, however, the basic root of the result $[\partial z^N/\partial n] > [\partial z^S/\partial n]$, for $n \geq 2$, stems from the fact that the level of the representative z_f^* is sufficiently higher in the Cournot-Nash fishery, versus its level in the Stackelberg oligopoly, such that the positive difference between both z_f^* solutions more than compensate the combined effect from (i) the higher marginal reduction in the representative z_f^* in the Cournot-Nash setting (again vs. the Stackelberg case) and (ii) the absence of reductions in the leading firm's effort z_L, as she optimally reacts to an increase in n, when this firm has Stackelberg leadership attributes and the harvesting technology is such that $k=d=1$[16].

(5.E) An optimality yardstick: the first best case.

In order to evaluate the overfishing proposition we need to define an explicit optimality benchmark. In chapter 4 we defined an *ideal* social planner, institutionally costless and as equally informed as private firms, who has *full* control over the industry's total harvesting fleet. Given this definition, the *ideal* planner will fully internalize the congestion effects arising from $\gamma > 0$. We call this case the first best planning solution.

Therefore, the planner's optimization problem consists in maximizing the industry's *total* profits, in each time period[17], by choosing the optimal fishing efforts

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[15] See a complementary analysis in section 5.H

[16] Note that the marginal impact $[\partial z^E/\partial n]$, with E= S,N to denote the equilibrium type, is equivalent to $\{\partial z_L/\partial n + z_f + n(\partial z_f/\partial n)\}$, given that $z^E = z_L + nz_f$.

[17] Recall that all time periods are identical in this model, hence we can describe the optimization problem as a fully static one.

for different productivity type firms. Let us retain the *symmetry* assumption among follower firms. If $0<d<1$, the representative follower firm f corresponds to the low-productivity type. Retain the notation for her fishing effort as z_f. Similarly, denote the effort of the high-productivity firm by z_L. Suppose that price variables p and w are the same as in the previous oligopoly equilibria. Therefore, the planner's problem is:

$$\max_{z_L,\, z_f} W = p(h_L + \sum_{f=1}^{n} h_f) - w(z_L + \sum_{f=1}^{n} z_f) \tag{23}$$

subject to $z_L \geq 0$, $z_f \geq 0$ and, given the assumption of $k=1$:

$$\begin{aligned} h_L &= \alpha z_L - \beta z_L^2 - \beta z_L \sum_{f=1}^{n} z_f \\ h_f &= d\left[\alpha z_f - \beta z_f^2 - \beta z_f \left[z_L + \sum_{\substack{i=1 \\ i \neq f}}^{n-1} z_i\right]\right] \end{aligned} \tag{24}$$

The first order conditions $(\partial W/\partial z_L)=0$ and $(\partial W/\partial z_f)=0$ define the following system of equations that describes the optimal choices for z_L and z_f:

$$z_L^{*} = \frac{1}{2\beta}\left[\alpha - \frac{w}{p}\right] - \frac{(1+d)n}{2} z_f^{*} \tag{25}$$

and

$$z_f^{*} = \frac{1}{2\beta}\frac{1}{n}\left[\alpha - \frac{w}{pd}\right] - \frac{1+(1/d)}{2}\frac{1}{n} z_L^{*} \tag{26}$$

As expected, when productivity differentials disappear ($d=1$) solutions (25) and (26) are fully equivalent. In this case, all N firms are fully symmetric and the industry's total effort is simply $(n+1)z_i^{*}$, with z_i^{*} denoting the representative firm's equilibrium effort. Therefore, when d=1 the optimal industry's total effort in our first best welfare case is:

$$z^{W1}(k=1,\ d=1) = \frac{1}{2\beta}\left[\alpha - \frac{w}{p}\right] \tag{27}$$

Looking at industry's total effort solutions for the Stackelberg and Cournot-Nash equilibria (see Tables 5.1 and 5.2), when k=1 and d=1, it is straightforward to verify that $z^S=[(2n+1)/(n+1)]z^{W1}$ and $z^N= [2(n+1)/(n+2)]z^{W1}$. Proposition 1 has already shown that $z^S(k=1) > z^N(k=1)$, $\forall$d feasible. And we know that the ratio $[2(n+1)/(n+2)] > 1$, $\forall n \geq 1$. Therefore, we can state:

Proposition 3:

When k=1 and d=1, both the Stackelberg and the Cournot-Nash equilibria imply higher industry's total fishing efforts than the optimal total efforts under the centralized decision of an institutionally costless and as equally informed (first best) welfare planner as private firms. This implies that in the Stackelberg and Cournot-Nash equilibria we encounter overfishing outcomes. Given the result stated in Proposition 1, the overfishing divergence from Pareto optimality is higher in the case of the leader-follower setting. Therefore, $z^S > z^N > z^{W1}$ under the conditions of this proposition.

What will occur with the first best welfare solution when harvesting firms with different productivity types are allowed to exist? That is, one high productivity firm with effort z_L, and n symmetric lower productivity firms ($0<d<1$), with a representative effort z_f. To answer this, we need to solve the system (25)-(26) for (z_L^*, z_f^*). Having done so, we initially find that the solution to this system implies that $z_L^* < 0$ and $z_f^* > 0$. But we know that negative effort solutions are neither feasible nor sensible within our model. Therefore, economic intuition suggests that in this case, given the technological assumptions such that k=1 (hence $\gamma > 0$), $0<d<1$, and the feasible space of solutions for the planner's problem ($z_i \geq 0$, i=L,f), it is not Pareto optimal that *both* types of firm (high/low productivity) show *positive* effort levels.

Instead, in the first best welfare solution only one type of firm is allowed to harvest. Hence, the first best planning benchmark corresponds to a corner solution.

The reason for this is that, by stopping the fishing activities of one of the two types of harvesting firms[18], the first best planner can reduce congestion effects and, hence, can increase the marginal harvesting productivity of the remaining firms. The active firm will correspond, unsurprisingly, to the high productivity type. In fact, by setting the representative fishing effort $z_f=0$, the first best planner not only keeps the higher productivity firm active, but also fully avoids the congestion externality. Therefore, in this case the sensible first best welfare equilibrium will imply $z_L^*>0$ and $z_f^*=0$. The Pareto optimal policy implies that the high productivity firm concentrates all the industry's fishing efforts[19]. By contrast, each firm f (lower productivity type) will be ordered to stop harvesting operations.

The previous reasoning implies that the industry's total fishing effort, that is chosen by this welfare planner, is exactly equivalent to the solution in equation (27)[20]. Therefore, we have backtracked to the outcome that is valid for a single productivity type firm and hence to the corollary of a private oligopoly overfishing that was stated in Proposition 3.

Consequently, given the technological assumption such that $k=1$ (hence $\gamma>0$), in this model we will always encounter overfishing outcomes if private oligopoly equilibria are compared with the first best planning solution. This result is due to the full control powers (over the industry's harvesting fleet) that the welfare

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[18] Recall that the assumption of full symmetry across type f firms, together with the exogeneity of the number n in our model, do not allow the planner to discriminate between type f firms. He can either allow them all to produce with identical effort levels, or to prevent them all from harvesting x. Our planner does not have any intermediate choices at all.

[19] Bear in mind that in this model we have not specified fishing capacity as a binding constraint for each firm's fishing effort choice problem.

[20] Set $z_f^*=0$ in solution (25).

planner is vested with in this modelling setting. In fact, the first best welfare planner can always adjust the operations of the harvesting fleet to an extent such as to fully eliminate any congestion problem.

(5.E.1) The first best welfare solution when $k \neq 1$.

We now analyse if $k \neq 1$ implies a change in the previous result that the first best planning solution coincides with the corner solution: $\{z_f=0,\ z_L=z^{W1}\}$. Let us focus on the optimal *distribution* of a given industry's total fishing effort, denote the latter by z ($z=z^{W1}$), between the two productivity types of firms, f and L, rather than on finding out the specific optimal *level* of z when $k \neq 1$. To simplify, assume the case of a duopoly fishery with firm L denoting the higher productivity type ($d=1$) and f the lower productivity type ($d<1$).

Looking at the planner problem (23)-(24), we can see that the optimal shares of firm f's and firm L's fishing efforts, in the industry total effort z, are given by combinations (z_f,z_L) that maximize industry total harvest $H= h_f+h_L$. Given the price information (p,w), the planner chooses the optimal *levels* of z_f and z_L among the former combinations (z_f,z_L).

The optimal distribution of a given level of total fishing effort z, among firms L and f, is characterized by the following planner problem:

$$\max_{z_L}\ H=h_L+\ h_f=\alpha z_L-\beta z_L^2-\gamma z_L(z-z_L)+d\alpha(z-z_L)-d\beta(z-z_L)^2-d\gamma z_L(z-z_L) \tag{28}$$

where we have written $z_f= (z-z_L)$, given that in this case we consider a *constant* level of total fishing effort z.

Assuming that the parameter values imply that the strict concavity of H with respect to z_L is fulfilled, $\partial H/\partial z_L=0$ characterizes the solution to problem (28). Note that when $\beta=\gamma$ ($k=1$) and $d=1$, $\partial H/\partial z_L=0$ for any combination $(z_L;z-z_L)$. In this case the allocation of a given industry total effort among individual firms does not affect total output H and, hence, the only relevant economic problem is to find out the optimal level of z (equation 27).

If $\beta>\gamma$ (hence $k<1$), we know that $[\partial^2H/\partial z_L^2]=2(d+1)(\gamma-\beta)<0$. This implies a declining marginal harvesting productivity as z_L increases. When $d=1$ we also know that $[\partial H/\partial z_L]=2(z-2z_L)(\beta-\gamma)>0$ for any $z_L<(z/2)$. Hence, when $k<1$ and $d=1$ the planner *first best* allocation ($\partial H/\partial z_L=0$) is to set $z_L=z_f=(z/2)$. If d falls, the optimal share of z_L in the total effort z should increase. Could it happen that for a sufficiently small $d>0$, the planner would decide to choose full specialization ($z_L=z$)?

We know that with $\beta>\gamma$, invariably $[\partial^2H/\partial z_L^2]<0$. Hence, if there exists a range of parameter values, with $d<1$, such that $[\partial H/\partial z_L]>0$ for a positive value of z_L, with $z_L=z$, the best effort allocation should be full specialization in the higher productivity firm L. When $d<1$, we can write the marginal harvesting productivity of z_L as follows:

$$\frac{\partial H}{\partial z_L}= \alpha(1-d)+(z-z_L)[2d\beta-\gamma(1+d)]- z_L[2\beta-\gamma(1+d)] \tag{29}$$

With full specialization such that $z_L=z$, $[\partial H/\partial z_L]>0$ requires that:

$$0<z_L<\frac{\alpha(1-d)}{(\beta-\gamma)+(\beta-\gamma d)} \tag{29'}$$

Note that the ratio in the right hand side of (29') is always positive for $d<1$, $\alpha>0$ and $\beta>\gamma$. Hence, it is possible that for some parameter values the condition (29') be valid. In these cases, we would obtain that the first best planning solution coincides with full specialization such that $z_L=z$.

Let us now consider the case when $\beta<\gamma$ and hence $k>1$. Suppose first that $d=1$. In this case, $[\partial H/\partial z_L]>0$ requires that z_L be greater than z/2; but when $k>1$, invariably $[\partial^2H/\partial z_L^2]>0$. The latter condition implies increasing marginal fishing effort productivity. Hence, in this case the best effort allocation coincides with full specialization ($z_L=z$, $z_f=0$; or $z_L=0$, $z_f=z$)[21]. Recall that this was the best first solution in the previous section when $k=1$ but $d<1$. We can generalize the latter saying that if $\beta \leq \gamma$ and $d<1$, then the best allocation is to set $z_L=z$ and $z_f=0$. In fact, if $\beta<\gamma$ we know that the marginal productivity of fishing effort will be increasing. Therefore, it will be convenient for the planner to specialize production in only one firm. Given this, when $d<1$, the planner should choose the higher productivity firm, that is, $z_L=z$.

In summary, the first best planning solution implying full specialization $\{z_L^*>0,\ z_f^*=0\}$ is not a general rule for all the combination between k and d values. Nonetheless, as the relative size of the congestion externality parameter increases with respect to β, and the relative productivity level of firm f decreases (d falls), the possibility that the first best planning solution implies full specialization ($z_L=z$ and $z_f=0$) increases.

Let us now consider an extension of the welfare planner's problem. Until now our discussion has assumed that the social planner has full control over the total harvesting fleet that operates in the common pool and multi-firm fishery. This assumption may be quite restrictive, and it could imply a highly idealized optimality benchmark. If the social planner faces additional binding constraints to solve problem (23)-(24), for example, due to information costs to fully control the industry's total harvesting fleet, the first best optimality benchmark can overestimate the magnitude of the oligopoly overfishing outcomes. The next section offers an illustration of this point.

(5.F) A second best welfare solution.

Suppose a second best welfare problem that consists of a planner that has only partial control over the harvesting fleet that operates in a restricted entry fishery. Assume

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[21] Because $d=1$, firms f and L are identical. Hence the planner is indifferent between choosing firm f or firm L as the single active harvesting firm.

that the planner can only control the fishing effort z_L of the more productive firm. Imagine that information costs prevent the direct control of the representative firm f's fishing effort z_f[22]. Firm f will continue to behave in a Cournot-Nash fashion. We will assume that the social planner behaves as a Stackelberg leader, in the sense of using z_L as a credible signalling to affect the fishing behaviour of the representative firm f. The planner's objective will continue to be the maximization of the industry's total profit (rather than just the firm L's profit). We can think of this case as a 'partial rationalization' fishing policy, given a public sector's partial control of the common pool fishery, through the management of one harvesting firm under direct public sector control.

For the sake of simplicity, let us consider the case of a duopoly fishery (n=1). Let us also maintain the technological assumption such that k=1. Firm f's problem is described by equation (5). Hence, firm f's Cournot-Nash behaviour implies that her optimal fishing effort z_f, conditional on the planner's signalling policy z_L, is given by equation (7). Given that k=1=n, equation (7) can be rewritten as:

$$z_f = \frac{1}{2\beta}\left[\alpha - \frac{w}{pd}\right] - \frac{z_L}{2} \tag{30}$$

Again the condition $z_f \geq 0$ implies restrictions on the parameters of the model. For instance, note that, even if $z_L=0$, $(1/2\beta)[\alpha - (w/pd)]$ must be positive in order that firm f be active.

The planner's problem is:

[22] Suppose, for instance, that the fishing effort of the representative firm f (the lower productivity type) is costly to monitor and to control because of the small scale of operation of type f firms.

$$\max_{z_L} W = p(h_L + h_f) - w(z_L + z_f) \tag{31}$$

subject to the harvesting technologies in equation (24), with n=1, and $z_L \geq 0$. Assuming that the strict concavity of W with respect to z_L is fulfilled[23], condition $(\partial W/\partial z_L)=0$ characterizes the planner's solution. Solving $(\partial W/\partial z_L)=0$, and using the fact that the planner knows the follower's reaction function given by (30), such that $\partial z_f/\partial z_L = -1/2$, we obtain:

$$z_L = \frac{1}{\beta(3-d)}\left[\alpha(2-d) - \frac{w}{p}\right] - \left[\frac{2}{3-d}\right] z_f \tag{32}$$

This equation shows the planner's optimal fishing effort policy conditional on the value of the follower's fishing effort z_f; but the planner knows that z_f is given by equation (30). Therefore, by combining the information in (30) and (32) we obtain the equilibrium values for z_f and z_L. Appendix 5.2 shows the second best welfare equilibrium in comparative terms with respect to the Stackelberg, Cournot-Nash, and first best welfare duopoly equilibria. Note that when we impose the condition that d=1, we obtain the duopoly equilibria shown in Table 5.4.

Notice that in the duopoly case with d=1 the industry's total fishing effort is the same in the first best and second best welfare solutions. In the latter case the first best solution is achieved because the planner opts for setting $z_L=0$. By doing so he fully avoids congestion problems, as in the previous welfare exercise (when k=1 and d<1; or when k>1 and d≤1), making the follower firm the sole owner of the common pool fishery; hence the follower firm chooses the first best Pareto efficient total fishing effort.

[23] This concavity condition only requires that the parameter values be such that $(\partial W/\partial z_L)>0$ for a positive solution z_L^*, because always $(\partial^2 W/\partial z_L^2)<0$ in this case.

Table 5.4: Duopoly Equilibria

(k = 1; d = 1; n = 1)

	STACKELBERG	COURNOT-NASH	WELFARE 1st - best	WELFARE 2nd - best
$z^{industry}$	$\frac{3}{2}\frac{1}{2\beta}\left[\alpha - \frac{w}{p}\right]$	$\frac{4}{3}\frac{1}{2\beta}\left[\alpha - \frac{w}{p}\right]$	$\frac{1}{2\beta}\left[\alpha - \frac{w}{p}\right]$	$\frac{1}{2\beta}\left[\alpha - \frac{w}{p}\right]$
z_L	$\frac{1}{2\beta}\left[\alpha - \frac{w}{p}\right]$	$\frac{2}{3}\frac{1}{2\beta}\left[\alpha - \frac{w}{p}\right]$	$\frac{1}{4\beta}\left[\alpha - \frac{w}{p}\right]$	0
z_f	$\frac{1}{4\beta}\left[\alpha - \frac{w}{p}\right]$	$\frac{2}{3}\frac{1}{2\beta}\left[\alpha - \frac{w}{p}\right]$	$\frac{1}{4\beta}\left[\alpha - \frac{w}{p}\right]$	$\frac{1}{2\beta}\left[\alpha - \frac{w}{p}\right]$

With $n>1$ the second best planner would not be able to achieve the first best solution by simply setting $z_L=0$, because the remaining oligopoly firms will achieve a Cournot-Nash equilibrium. In this case the welfare planner will face a trade off between (i) choosing a higher $z_L^*>0$ in order to preempt and to reduce follower firms' fishing efforts with lower harvesting productivity, and (ii) the resulting congestion effects which will be triggered by the choice of a higher $z_L>0$. The planner's z_L decision has to optimally balance both effects. In section 5.H we explore these ideas.

In this section we maintain the assumptions such that $k=n=1$. Let us now focus on the case when $d<1$. In this setting, it is not clear *a priori* whether or not the second best planner can still achieve the first best solution. If he aims to fully avoid the congestion externality effect, by setting $z_L=0$, he has to accept that the lower productivity firm will be the active harvesting unit. This implies a cost in terms of a lower harvesting productivity from fishing effort units. Let us then study how the second best planner chooses z_L for different values of d. We will compare the resulting industry equilibrium with those obtained in the Stackelberg, Cournot-Nash and first best welfare equilibria.

We explore this issue by developing a numerical simulation exercise. Looking at equation (30), we confirm that $(1/2\beta)[\alpha-(w/pd)]>0$ is a necessary condition in order that firm f be active ($z_f>0$). Let us define some arbitrary parameter values such that this condition is valid for at least a range of the feasible d values ($0<d\leq 1$). Assume that $\alpha=11$, $\beta=1/2$ and $(w/p)=1$[24]. Hence the first best industry fishing effort solution corresponds to a value of 10 (equation 27). Given these parameter values, equation (30) becomes:

$$R_f(d) \equiv \quad z_f = \left[11-\frac{1}{d}\right] - \frac{z_L}{2} \tag{30'}$$

whereas equation (32) is equivalent to:

$$R_L(d) \equiv \quad z_f = (21-11d) - \left[\frac{3-d}{2}\right] z_L \tag{32'}$$

We denote the former reaction function by $R_f(d)$ and the latter by $R_L(d)$. These two equations define the second best welfare equilibrium $\{z_L^{W2}, z_f^{W2}\}$ as a function of parameter d. Figure 5.1(a)-(b) represents this case. In what follows we first describe the prevailing second best welfare equilibria $\{z_L^{W2}, z_f^{W2}\}$ for different values of d and, second, we compare them with the other industry equilibria that were analysed in previous sections.

[24] Note that these parameter values satisfy the strict concavity condition that is required to fulfil in order that $(\partial V_i/\partial z_L)=0$ characterizes the unique optimal effort solution z_L for a decision maker that has Stackelberg signalling attributes (with i representing either the Stackelberg private firm leader or the second best welfare planner).

(5.F.1) Deriving the second best welfare equilibria as a function of d.

Point A in Figure 5.1(a) represents the first best planning solution when $d<1$ and $k=1\{z_L=10,\ z_f=0\}$. Point A' represents the second best planner's choice when $d=1$. As d falls from 1, the locus R_f moves with constant slope towards the origin O. The locus R_f crosses point O when $d=1/11$. This means that when $d\leq 1/11$ firm f is *always* inactive; hence the planner, for any $z_L\geq 0$, behaves as a sole owner. Therefore, for this range of d values the first best solution $z^{W1}=z_L+z_f=10$ is always achieved. Even more, we can deduce that the second best planner will be able to achieve the first best solution as long as $d\leq 1/6\cong 0.167$. The logic underlying this result is as follows.

First, note that the locus R_L moves away from the origin O as d falls from 1: its intercept at axis z_f, as well as the absolute value of its negative slope, increases as d becomes lower. Second, as d increases from $d=1/11$ locus R_f moves away, with constant slope, from point O. When $d=1/6$, locus R_f crosses point A. This means that, for $1/11<d\leq 1/6$, the interception between both loci must occur at a point such that $z_L>0$ and $z_f<0$. Hence the constraint $z_i\geq 0$, $i=L,f$, implies that in this range of d values the planner must optimally choose a $z_L>0$ such that $z_f=0$. We can easily check that for $1/11<d\leq 1/6$, it must be true that $0<z_L'(d)\leq 10<z_L''(d)$; where z_L' and z_L'' values denote, respectively, the points where the loci $R_f\equiv z_f=g(z_L';d)=0$ and $R_L\equiv z_f=q(z_L'';d)=0$, with the functions g(.) and q(.) given by equations (30') and (32'), respectively. But, for $1/11<d\leq 1/6$, the social planner will choose none of these two z_L values. Instead, he will choose $z_L=10$.

Suppose that $d=d'$, with $1/11<d'<1/6$, and locate in Figure 5.1(a) a point such as $z_L=z'<10$ such that $R_f\equiv z_f=g(z';d')=0$. For any $z_L>z'$ the follower firm will set $z_f=0$; hence for any $z_L>z'$ the planner will be able to behave as the sole owner of the common pool fishery. And we know that in this case the optimal fishing effort policy is $z_L=10$. Therefore, for any $0\leq d\leq 1/6$ the second best planner achieves the first best solution.

On the other hand, when $d=3/13\cong 0.23$ the loci R_f and R_L intercept at point C such that $z_f^{W2}=0$ and $z_L^{W2}\cong 13.33$ (Figure 5.1(a)). For $3/13<d<1$, we can easily check in (28') and (30') that both (second best) effort solutions z_f^{W2} and z_L^{W2} are positive. A typical second best welfare equilibrium for $3/13<d<1$ is one such as point D. As d moves away from $d=3/13$ and gets closer to $d=1$, the industry equilibrium gets nearer of point A'. Hence, as d increases z_L^{W2} falls, whereas z_f^{W2} increases. For the cases when $3/13<d<1$, solutions $\{z_L^{W2}, z_f^{W2}\}$ are given by the corresponding expressions in Appendix 5.2.

Finally, which are the second best welfare equilibria for $1/6<d<3/13$? In these cases we know that the loci R_f and R_L intercept at points such that $z_L>0$ and $z_f<0$. Hence, in these cases z_f must be zero. But in this range of d values, any specific value of d implies that $z_f=0$ for two values of z_L (see Figure 5.1(a)): for $10<z_L''(d)<13.33$ such that $R_f\equiv z_f=g(z_L'',d)=0$, and for $\hat{z}_L(d)>13.33$ such that $R_L\equiv z_f=q(\hat{z}_L,d)=0$. Note that in this range of d values, $z_L=10$ implies $z_f>0$ (given by the reaction function R_f). Hence in this case the second best planner cannot achieve the first best planning solution. Which fishing effort will the planner choose, $\hat{z}_L(d)$ or $z_L''(d)$?

The planner will choose $z_L''(d)$ because, within the range $1/6<d<3/13$, the sign of $\partial W/\partial z_L$ is negative for any $z_L>z_L''(d)$, with W given by equation (31). Notice that, for $\hat{z}_L\geq z_L>z_L''$, $\partial W/\partial z_L$ must be evaluated subject to the fact that $z_f=0$ and $[\partial z_f/\partial z_L]=0$. Doing so, we find that any $z_L>10$ implies $\partial W/\partial z_L<0$. Therefore, in this range of d values the best that the planner can do is to set $z_L=z_L''(d)$.

Figure 5.1(b) shows the resulting fishing effort optimal choices, as a function of d values, for the second best planner and the follower firm. The industry curve shows the aggregate fishing effort $z^{W2}=z_L^{W2}+z_f^{W2}$. In order to obtain comparative results, let us now solve the simulation exercise for the private Stackelberg and Cournot-Nash equilibria.

(5.F.2) Private Stackelberg duopoly equilibria.

Figure 5.2(a)-(b) shows the corresponding Stackelberg equilibria as a function of d. $R_f(d)$ is the same function as that in the second best welfare problem, that is, $R_f \equiv z_f=(11-(1/d))-z_L/2$. We obtain R_L by imposing on equation (9) the set of assumptions that we use in this section ($k=n=w/p=1$, $\beta=0.5$, $\alpha=11$). Hence $R_L \equiv z_f=20-(3/2)z_L$. This equation characterizes the Stackelberg leader's optimal effort policy conditional on the value of the follower's fishing effort. Due to the same logic that was analysed in the previous case of a welfare planner with Stackelberg leadership attributes, the (private) Stackelberg equilibria $\{z_L^S, z_f^S\}$ are as follows (see Figure 5.2(a)):

For $0<d\leq 1/6$, $z_f^S=0$ and $z_L^S=10$ (point A); hence in this range of d values the (private) Stackelberg duopoly achieves the first best welfare solution. At $d=3/13$, R_f and R_L intercept at point C ($z_L^S=13.33$; $z_f^S=0$). For $d>3/13$, the Stackelberg equilibria move upwards and along curve R_L. For $3/13<d<1$, a typical equilibrium point is one like D. When $d=1$, the Stackelberg equilibrium locates at point E ($z_L^S=2z_f^S$). For $1/6<d'<3/13$, the Stackelberg equilibrium is given by $R_f(z_f^S=0;d';z_L^S)$, with $10<z_L^S<13.33$ (point B).

Figure 5.2(b) represents the resulting fishing effort solutions (for the Stackelberg leader, the follower firm, and the industry equilibrium) as functions of parameter d.

(5.F.3) Cournot-Nash duopoly equilibria.

Consider the case when both firms behave as Cournot-Nash players. L denotes the higher productivity firm ($d=1$), whereas f denotes the lower productivity type ($d\leq 1$). Each firm i's ($i=f,L$) optimal fishing effort is characterized by equation (6)[25] subject to (4) and the parametric assumptions in this section. From this we can deduce the reaction function of each firm, R_f and R_L. Hence, the Cournot-Nash equilibria are

[25] Replace f by i in (6) in order to obtain z_i^* for $i=L$.

given by the equations $R_f(d) \equiv z_f = (11-(1/d)) - z_L/2$, and $R_L \equiv z_f = 20 - 2z_L$. Figure 5.3 (a)-(b) represent them.

The equilibrium points $\{z_L^N, z_f^N\}$ are as follows (see Figure 5.3(a)). Note that for $d=1/6$, locus R_f crosses point A ($z_f^N=0$; $z_L^N=10$) which implies the first best planning solution when $k=1$ and $d<1$. For $1/6<d\leq 1$, z_f^N and z_L^N are both positive with the equilibrium points moving along curve R_L, going from A towards E as d increases (z_f^N getting higher and z_L^N becoming lower). Point E is the symmetric Cournot-Nash equilibrium ($d=1$), with the representative firm i's optimal fishing effort $z_i=20/3$. When $d=1/11$, locus R_f crosses the origin O; hence, for $d\leq 1/11$, firm f becomes inactive and therefore firm L is the sole owner of the common pool fishing grounds. Hence, for $d\leq 1/11$ the Cournot-Nash equilibria will coincide with the first best planning solution, with $z_f^N=0$ and $z_L^N=10$. Finally, when $1/11<d<1/6$ locus R_f crosses the z_L axis between points O and A. As analysed previously, this implies that $z_f^N=0$. In this range of d values, $z_f^N=0$ requires that $z_L>0$. Given the fact that $z_f=0$ and $\partial z_f/\partial z_L=0$ in this range of d values, we hence deduce that the optimal firm L's effort policy is to set $z_L=10$. Figure 5.3(b) represents the fishing effort solutions as a function of d.

(5.F.4) Comparative analysis.

Let us now combine the results obtained in the previous analysis and study the implications in terms of overfishing outcomes for the different duopoly equilibria that we have considered.

Figure 5.4(a) represents the total fishing effort solutions for the private Stackelberg case, for the second best welfare exercise (denoted by welfare 2B), and for the Cournot-Nash duopoly fishery. Figures 5.4(b)-(c) represent, for these three cases, the corresponding fishing effort solutions for the leading firm L and for the follower (lower productivity type) firm f. Recall that with $k=1$ and $d\leq 1$, the first best welfare solution for total fishing effort is equal to 10.

In Figure 5.4(a) we observe that for $0<d\leq 1/6$ in the three cases of duopoly equilibria the first best welfare solution is achieved. This occurs because within this range of d values the harvesting productivity of firm f's fishing efforts is sufficiently lower versus firm L's harvesting productivity such that it is optimal for f to be inactive. Hence firm L can behave as a sole owner and, therefore, she chooses the first best total fishing effort.

Let us now focus on the relative fishing effort solutions between the private Stackelberg and (second best) welfare duopoly equilibria. For $1/6<d\leq 3/13$, z^{W2} still coincides with the Stackelberg total effort z^S; but both are now higher than 10 because within this range of d values the Stackelberg leading firm needs to increase z_L in order to maintain $z_f=0$. For the second best planner this is a Pareto efficient fishing policy because by doing so he is avoiding congestion problems by stopping the fishing activity of firm f which still has a relatively low harvesting productivity.

However, insofar as $d>3/13\cong 0.23$, implying that z_f begins to be positive while firm f is competing with a firm L which has Stackelberg leadership attributes, we start to observe a positive difference between the private Stackelberg total fishing effort z^S and the second best welfare total effort solution z^{W2}. As d gets higher, the overfishing gap $(z^S-z^{W2})>0$ increases. This occurs because the private Stackelberg leader's fishing effort decreases at a lower rate, versus the reduction of z_L with the second best welfare planner, as d gets higher. Consistently, as d increases the follower firm increases her effort z_f at a lower rate in the private Stackelberg duopoly fishery, versus the second best welfare case. The strategic preemption of the private Stackelberg leader, in terms of reducing the rival firm's fishing effort, is clearly higher versus the social planner's effort choices. This is so because the second best social planner internalizes, while the private leader does not, the marginal social benefits of increasing the share of firm f's fishing effort z_f in total effort z^{W2} as firm f becomes more productive. When both firms' harvesting productivity becomes equivalent $(d=1)$, the second best welfare planner chooses to keep firm f as the active harvesting unit, because by stopping fishing efforts from firm L he can avoid the congestion externality problem without incurring in fishing effort's marginal productivity losses. With $d=1$, firm f becomes the sole owner of the fishery and the first best total effort ($z^{W2}=z^{W1}=10$) is achieved.

In the case of the Cournot-Nash duopoly we confirm our previous result (proposition 3) in terms of a consistent *lower* total fishing effort, for all d greater than 1/6, versus the case of the private Stackelberg fishery. For $d>1/6$, z_f starts to be positive in the Cournot-Nash duopoly and firm f's fishing effort becomes consistently higher in the Cournot-Nash case than in the private Stackelberg fishery; while the opposite occurs with the fishing effort from the leading firm L. This is a result of the strategic preemption ability that the leading firm L has when she is endowed with Stackelberg leadership attributes.

An interesting result is obtained when we compare the Cournot-Nash equilibrium with the second best welfare solution. We can see in Figure 5.4(a) that $z^{W2}>z^{N}$ for $1/6<d<0.61$, whereas $z^{N}>z^{W2}$ for $0.61<d\leq 1$. Only the latter range of d values is consistent with the overfishing outcome that we stated in proposition 3. Why in the range $1/6<d<0.61$ the Cournot-Nash fishery implies a higher industry fishing effort than the optimal total effort for the second best planner?

Note that for $1/6<d<0.61$, $z_L^{W2}>z_L^{N}$ and hence $z_f^{W2}<z_f^{N}$. This implies that, in this range of relatively low d values, the planner prefers higher fishing efforts from the more productive firm L than the effort levels that firm L chooses if she has no Stackelberg signalling abilities. The resulting higher total fishing effort in the second best welfare exercise must be the result of net (social) marginal productivity gains arising from a higher share of firm L in the industry's total fishing effort.

As d increases, however, the social productivity gains, arising from a higher share of z_L in total fishing effort z^{W2} (versus the corresponding share in the Cournot-Nash case), become smaller because firm f's productivity gets closer to firm L's fishing effort productivity. Simultaneously, as d increases (and so the optimal z_f) the congestion problems that arise from not reducing z_L more quickly become a more binding technological constraint for each firm's harvesting productivity. Hence, the social planner will prefer a quicker reduction of z_L versus the choice of the Cournot-Nash firm L. In fact, as d approaches the value of 1, the planner prefers to stop his own harvesting (setting $z_L^{W2}=0$) so as to maximize the total (optimal) production that can be obtained by a sole owner who faces no congestion problems. The Cournot-Nash firm L, however, does not internalize the higher congestion externality that her higher effort z_L^N (versus z_L^{W2}) produces. This is the reason why in the range of $0.61 < d \leq 1$ the Cournot-Nash fishery will imply overfishing versus the effort choices of the second best welfare planner.

Finally, we can easily observe in the graphics referred to above how the use of first best optimality yardsticks can sometimes distort the evaluation of the magnitude of overfishing results in common pool oligopoly fisheries. We have seen that this type of distortion can, on occasions, even imply a change in the sign of the over(under)production result; for example, in our simulations, for the range $1/6 < d < 0.61$, when we compare the Cournot-Nash solution with the second best welfare benchmark.

(5.G) Duopoly equilibria with $k \neq 1$.

This section explores the robustness of the overfishing ranking in Proposition 3 (which considers $k=1$) with regard to changes in the relative technological size of the congestion externality effect. We will obtain a generalization of the previously derived overfishing ranking, for k values between 0 and 1. For the sake of simplicity, we assume: (i) a duopoly fishery ($n=1$) and (ii) no productivity differences ($d=1$) between firm L and firm f. We will only consider k values such that $0 \leq k \leq 1$. There are two reasons for the latter choice.

First, we want to exclude the case when the first best welfare solution implies full specialization. In section (5.E) we saw that if $k>1$ the first best welfare planner chooses a corner solution ($z_L=z^{W1}$ and $z_f=0$; or $z_L=0$ and $z_f=z^{W1}$). By contrast, with $k<1$ and $d=1$ we saw that the first best planner's optimal choice implies $z_L=z_f=z^{W1}/2$. This will be the case in this section and, hence, we will calculate the first best total effort z^{W1} for k values between 0 and 1.

Second, we want to be sure that the strict concavity condition for the optimization problem of a Stackelberg leading firm is fulfilled. The fulfillment of this concavity condition ensures that the Stackelberg leader's choice for her optimal fishing effort policy will represent a unique maximum solution. Within the range $0 \leq k \leq 1$, the previous concavity condition is invariably true[26]. This applies to the case of the private Stackelberg duopoly as well as to the optimization problem of the second best welfare planner.

We develop a numerical simulation analysis maintaining the parameter values such that $\alpha=11$, $\beta=1/2$ and $(w/p)=1$. Appendix 5.3 describes the derivation of the Stackelberg, Cournot-Nash, first best welfare, and second best welfare duopoly solutions as functions of parameter k. Figure 5.5(a) represents the solutions for the industry's total fishing effort, as a function of k, in these four concepts of duopoly equilibria. Figure 5.5 (b)-(c) represent the corresponding effort solutions for the leader (firm L) and the follower (firm f).

In Figure 5.5(a) we observe that when $\gamma=0$, and hence $k=0$, the four duopoly equilibria imply the same total effort solution, call it z, equal to a value of 20; with each duopolist using the same effort level $z_i=z/2=10$. In this case, the absence of congestion effects implies that the duopoly equilibria always coincide with the first best planning solution. Why is this so? With no technical externalities, the

[26] In section 5.E we saw that the fulfillment of this concavity condition requires that $2-k \geq nk(k-1)$. With $n=1$, this inequality implies that $k \leq 1.41$. We simplify by taking the value of $k=1$ as the upper limit.

oligopolistic fishing firms always face *complete* markets in the fishery under analysis. In this case a leading firm with Stackelberg attributes cannot strategically preempt her rivals' fishing efforts by changing her own effort z_L; and Cournot-Nash conjectures now imply that the decision maker internalizes all the relevant productivity effects as she chooses her optimal fishing effort. Therefore, the resulting market equilibria are Pareto efficient.

When $k=1$, and $d=n=1$, Figure 5.5(a) confirms the results that we have already analysed in the previous sections. The first best and second best welfare solutions for total effort coincide, because in this case the second best planner stops his own harvesting, making firm f the sole owner and, hence, a Pareto efficient decision maker in this fishery. The Stackelberg and Cournot-Nash effort curves, when $k=1$, represent the overfishing ranking already proved.

For $0<k<1$ we obtain a consistent and robust overfishing ranking with respect to the results obtained, when $k=d=1$, in sections (5.E) and (5.F). In this range of k values, the resulting robust overfishing ranking implies that $z^{W1}<z^{W2}<z^{N}<z^{S}$, maintaining the same notation of previous sections[27] (Figure 5.5(a)).

In the four equilibria under analysis, the resulting industry's optimal total effort monotonically decreases as the technological size of the congestion externality effect increases, relative to β. However, the overfishing in the Stackelberg and Cournot-Nash settings unambiguously increases as the value of k gets higher in our simulation exercises. The latter result is equally valid if we compare the private oligopoly equilibria's total effort with the first best welfare yardstick z^{W1}, as when we consider the second best benchmark z^{W2}.

In terms of the leading firm L's optimal fishing effort (see Figure 5.5(b)), the four equilibrium solutions imply, for $0<k\leq 1$, that $z_L^{S}>z_L^{N}>z_L^{W1}>z_L^{W2}$ (the

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[27] The numerical simulation exercise implies unambiguous results in terms of this overfishing ranking, for each k value such that $0<k<1$.

numerical simulation results are unambiguous with respect to this ordering). Finally, with respect to the representative type f firm's optimal fishing effort (see Figure 5.5(c)), the four equilibria imply, for $0<k<1$, that $z_f^{W2}>z_f^N>z_f^S>z_f^{W1}$. Again the numerical simulation results are unambiguous in terms of this ordering. Let us briefly explore the logic underlying these results.

In the cases of the first best welfare and Cournot-Nash solutions, the monotonic reduction in the industry's optimal total fishing effort simply reflects the declining marginal productivity of the *representative* fishing firm i (recall that $d=1$ in this section) as the value of the congestion parameter γ increases. Figures 5.5(b)-(c) represent the declining optimal effort of the representative duopolist firm i, in the first best welfare and Cournot-Nash cases, as k increases. Notice, however, that in the first best welfare case the resulting representative firm i's effort solution implies a consistently lower optimal fishing effort than in the Cournot-Nash duopoly, for all $0<k\leq 1$. This occurs because the welfare planner fully internalizes the increasing congestion problem as $k>0$ becomes higher, whereas the Cournot-Nash firm only does it partially. If we consider the private Stackelberg duopoly solution for $0<k\leq 1$, we obtain firms' effort rankings which are consistent with the results that were analysed in sections (5.D), (5.E), and (5.F) for the case of $k=1$; that is, $z_L^S>z_i^N>z_i^{W1}$ and $z_i^{W1}\leq z_f^S<z_i^N$ (when $0<k\leq 1$).

In the cases of the second best welfare problem and the private Stackelberg fishery, the leading firm L faces an additional effect to the declining harvesting productivity effect, as the congestion parameter increases: the leader's harvesting preemption ability, *ceteris paribus*, increases; that is, invariably $\partial|\theta^L|/\partial\gamma>0$ (see equation (7)). In the case of the second best welfare problem, the planner uses his Stackelberg leadership ability in order to counteract the congestion problems that arise from a higher congestion parameter γ. Notice in Figure 5.5(b) the difference between the evolution of z_L^{W2} and the optimal effort policy z_L^S for the private

Stackelberg leader. Invariably $(z_L^s - z_L^{W2}) > 0$ for $0 < k \leq 1$, with this positive difference widening as k increases.

As the value of γ increases, and hence the value of k, the second best welfare planner monotonically reduces his fishing effort z_L^{W2}. By doing so, he helps to counteract the increasing congestion effect from a higher k and the resulting declining harvesting productivity of the follower firm f. As k gets nearer to $k=1$, the planner increases the rate of reduction of his own fishing effort and, by doing so, he starts to trigger an increasing pattern in the follower's optimal fishing effort (Figure 5.5(c)). When $k=1$, the planner sets $z_L^{W2}=0$ and makes the follower firm the sole owner of the fishery.

In the case of the private Stackelberg duopoly we observe a monotonic decline in the follower's optimal effort as k increases. This is partly due, as in the other duopoly equilibria, to the declining harvesting productivity of the follower firm as k increases. However, the rate of decline in z_f is faster in the private Stackelberg duopoly than in the Cournot-Nash and the second best welfare cases (see Figure 5.5(c)). This effect is even more evident as k gets nearer to $k=1$. The reason is that, as k increases, the harvesting preemption effect in favour of the private leading firm starts to increasingly compensate the declining marginal productivity effect that is faced by the private Stackelberg leader, as γ gets higher[28]. The strategic preemption

[28] We can write the leading firm's marginal harvesting productivity as:

$$\frac{\partial h_L}{\partial z_L} = \alpha + \left[\frac{\gamma^2}{2\beta}\right] z_L - 2\beta z_L - \gamma z_f$$

In this expression two factors depend on the value of γ: the positive factor represents the harvesting preemption effect, whereas the negative factor represents the direct (declining) productivity effect that stems from the congestion externality. The marginal impact of changes in γ is given by $\partial h_{zL}/\partial\gamma = kz_L - z_f$. The latter expression helps to understand why as k increases and z_f decreases, increases in γ will eventually produce positive effects on the leader's marginal productivity and, hence, they will eventually trigger an increasing pattern in the optimal level of z_L.

effect starts to dominate over the declining productivity effect from $k>0.59$[29]. As a result of this, starting from this value of k we observe an increasing pattern in the leading private firm's optimal fishing effort. The latter result implies that the follower firm's optimal effort starts to decline faster as k increases due to the higher total congestion effect faced by the latter firm.

In summary, in this section we have confirmed the overfishing ranking such that $z^{W1}<z^{W2}<z^{N}<z^{S}$, for k values greater than 0 and lower or equal to 1. The overfishing in the Stackelberg and Cournot-Nash duopolies, either measured with respect to z^{W1} or z^{W2}, unambiguously increases as the relative technological size of the congestion externality parameter increases, that is, as k gets higher.

(5.H) An increasing number of rival firms.

This section explores the impact of a higher value of *n* on the fishing effort solutions for firm L and the representative firm f (we keep symmetry among type f firms), and the resulting industry's total fishing effort, under the different equilibrium definitions considered in section (5.G). For simplicity we assume in this section $k=1$, given the robustness of the overfishing ranking, for $0\leq k\leq 1$, between the different oligopoly equilibria analysed in the previous section. We again consider a numerical simulation analysis, maintaining the same parameter values previously assumed, that is, $\alpha=11$, $\beta=1/2$ and $(w/p)=1$.

What do we already know in terms of total fishing effort solutions when $k=1$? First, with $k=1$ and $0\leq d\leq 1$, the first best industry's fishing effort is invariably equal to $z^{W1}=10$ (given the parameter values above specified) for all $n\geq 1$. Second, if $k=1$ and $d=1$, we know that $z^{S}>z^{N}>z^{W1}$ for all $n\geq 1$ (Proposition 3); and that the positive gap $(z^{S}-z^{N})$ decreases as the number of rival firms increases, for $n\geq 2$ (see comments to Table 5.3).

[29] The value $k=0.59$ corresponds to the minimum value of the equilibrium solution for z_L in the Stackelberg fishery, which in this section is equal to $z_L=10(2-k)/(2-k^2)$.

Third, we can also prove that when $k=1=d$ the second best welfare planner invariably sets $z_L^{W2}=0$ and, hence, $z^{W2}=nz_f^{W2}$ for all $n\geq 1$ (see Appendix 5.4). The latter result generalizes the second best welfare solution previously obtained for a duopoly fishery in section (5.F). However, we have seen in section (5.G) that the solution $z_L^{W2}=0$ does not generalize, when $d=1=n$, for k values lower than 1. We saw that $\partial z_L^{W2}/\partial k<0$ in a monotonic way. This is due to the planner's aim to counteract the higher congestion problem as k increases.

In this section we explore whether or not the solution $z_L^{W2}=0$ remains invariant, given that $k=1$, when d varies between 0 and 1 and the number of oligopolistic firms increases. We compare the resulting z_L^{W2} with the optimal fishing effort policy for a private Stackelberg leader. Finally, we study the resulting overfishing ranking between the Cournot-Nash, Stackelberg and second best welfare oligopoly equilibria.

We proceed as follows. Allowing for $0<d\leq 1$, we consider three arbitrary values of n (1;3; and 10) in our numerical simulations. This allows us to analyse the effects of a higher number of rival firms on the different oligopoly equilibria which are specified as a function of parameter *d*. Appendices 5.4 to 5.6 describe the derivation of the second best welfare, Cournot-Nash and Stackelberg equilibria as a function of parameters *n* and *d*.

Figures 5.6(a) and 5.7(a) represent the resulting industry's total effort in the three equilibria under study. We can observe that the range of d values that implies a *sole owner* solution in the three equilibria, that is $0\leq d\leq 1/6$, is invariant to the changes in the number *n* of rival firms. From $d>1/6$, the Cournot-Nash total fishing effort z^N monotonically increases as n gets higher (Figure 5.7(a)). In the cases of the Stackelberg and second best welfare equilibria, the effects on the industry's total efforts are more complex. Let us analyse them.

(5.H.1) More rival firms and Stackelberg leadership attributes.

In the oligopoly equilibria where one firm is endowed with Stackelberg leadership attributes (Stackelberg and second best welfare cases), increases in *n* widen the range of *d* values where the sole owner solution prevails (such that the equilibrium value of the representative z_f=0). Notice that in this range of *d* values the private Stackelberg and second best welfare solutions are fully equivalent (Figures 5.6(a)-(b)-(c)). With n=3, the upper limit for the validity of the sole owner solution is given by d=1/3; with n=10, the upper limit of this solution rises to d=6/11. Figure 5.6(b) shows that as *n* increases, the level of the leader's optimal effort z_L increases in this range of *d* values, in order to preempt fishing effort from the follower firms. Figure 5.6(c) shows the corresponding range of d values such that the equilibrium value of z_f=0. Why is this so?

For the private Stackelberg leader, a higher *n* implies a higher harvesting preemption power over the group of follower firms. This simply means that the leader can discourage fishing effort from a higher number of rivals (see comments on equation (8), given that k=1). By choosing a higher z_L^s in this range of *d* values, the Stackelberg leader is able to fully avoid the presence of congestion externality effects and the corresponding negative effects on his own marginal harvesting productivity.

As long as the sole owner solution prevails, the private leader and the second best welfare planner choose identical z_L. Therefore, in the range of *d* values where the sole owner solution prevails, it must be true that the full preemption of the representative follower's fishing effort (by means of setting a higher $z_L^{w2}(d)>0$ as n increases, such that $z_f(d)=0$) generates higher social benefits than the catch losses that result from the inactivity of type f firms. These net welfare gains balance the productivity gains that stem from the avoidance of an increasing congestion problem as *n* rises, versus the catch losses from inactive firms with (relative) harvesting productivity given by parameter *d*.

However, starting from a d value such that the equilibrium value of z_f becomes positive (with this d value such that $d=d(n)$, $d'>0$), the optimal fishing effort policies for the private Stackelberg leader and the second best welfare planner start to diverge. As long as $z_f>0$, we obtain that invariably $z^S>z^{W2}$, with $z_L^S>z_L^{W2}$ and, correspondingly, $z_f^S<z_f^{W2}$.

While both (private and social planner) Stackelberg leading firms reduce their corresponding optimal z_L when $z_f>0$ and d increases, the social planner does it in a quicker way (see Figure 5.6(b)) in order to take advantage of the increasing relative harvesting productivity of the representative follower firm. As d increases, the objective of avoiding congestion problems, by fully preempting the fishing efforts from type f firms, starts to lose priority relative to the higher catch performances that stem from allowing positive harvesting from type f firms with an increasing productivity. The gains from the latter effect increase as the number of type f firm increases. This explains the quicker rate of reduction in the optimal z_L^{W2} as n increases, provided that the level of d makes it socially worthwhile to allow the representative z_f to be positive.

Figure 5.6(c) represents the corresponding increasing levels of the optimal $z_f>0$ as the values of d get higher. Notice, however, that increases in n unambiguously reduce the optimal level of z_f for a given value of d, both in the Stackelberg and second best welfare cases. This result simply reflects the declining marginal productivity of type f firms as the number of rival firms increases, due to the increasing congestion externality problem.

Note also in Figure 5.6(b) the widening, as the value of n increases, of the range of d values where it is optimal for the second best planner to set $z_L^{W2}=0$. With $n=1$, this *shut down* policy is optimal only when $d=1$; when $n=10$, $z_L^{W2}=0$ is optimal for the range $0.756\leq d\leq 1$ (see Appendix 5.4). This implies that, as n gets higher, it becomes optimal for the second best welfare planner to fully sacrifice the use of his harvesting preemption ability in a wider range of d values, in order to allow for higher harvesting from a higher number of type f firms with a harvesting productivity *relatively* close to firm L's productivity.

Finally, Figure 5.6(d) shows the evolution of the Stackelberg overfishing gap, relative to the second best welfare yardstick[30], as d and n increases. With a duopoly fishery (n=1) we obtain a monotonic increase in the Stackelberg overfishing gap, as d increases, as long as the sole owner solution no longer prevails. Notice that when d=1 the overfishing outcome implies an industry's total effort which is 50% higher in the Stackelberg duopoly than in the second best welfare fishery.

With more follower firms, which are not under the control of the welfare planner, the Stackelberg overfishing gap becomes smaller. With n=10, the overfishing gap implies a Stackelberg total effort which is around 5% higher than the optimal z^{W2}. When n=3 or n=10, the welfare planner's shut down policy (setting $z_L^{W2}=0$ for relatively high values of d) triggers a declining Stackelberg overfishing gap as the values of d get nearer to d=1. This occurs because the second best welfare solution becomes equivalent to a Cournot-Nash equilibrium with n symmetric type f firm. This equivalence implies an increasing equilibrium's total effort as d increases in this range (Figure 5.6(a)) and a reduction of the positive difference with respect to a higher Stackelberg total effort.

In summary, the optimal policy $z_L^{W2}=0$ (valid when $d=k=1$, $\forall n \geq 1$) does not remain invariant when $d \neq 1$ and n changes. For relatively low values of d, the second best planner chooses an initially increasing $z_L^{W2}>0$ in order to fully avoid congestion problems. When the representative z_f becomes positive we obtain that $z^S > z^{W2}$, with $z_L^S > z_L^{W2}$ and $z_f^S < z_f^{W2}$. As d increases, both z_L^S and z_L^{W2} decreases, but the latter does so in a quicker way. This occurs because the social planner fully internalizes the social gains that stem from allowing an increasing harvesting from type f firms with

[30] The Stackelberg overfishing gap is measured as the percentual ratio $(z^S-z^{W2})/z^{W2}$. The overfishing measured in terms of the first best welfare yardstick can easily be observed in Figure 5.6(a). Recall that $z^{W1}=10$ for all d such that $0<d\leq 1$ and for all $n \geq 1$.

(relative) higher productivity. In a final stage, as *d* gets closer to 1, the social planner finds it optimal to shut down his own harvesting (setting $z_L^{W2}=0$). Finally, increases in the number of rival firms tend to reduce the Stackelberg overfishing gap, when the latter is measured with respect to the second best welfare yardstick.

(5.H.2) Cournot-Nash (under)overfishing.

In Figure 5.7(a) we can compare the Cournot-Nash industry' total effort with the first best welfare solution. We observe an increasing Cournot-Nash overfishing as *n* gets higher, provided that the sole owner solution is no longer valid. This result is close to standard (informal) economic intuition. If we now compare the Cournot-Nash solution with the second best welfare yardstick, the comparative results are less directly intuitive. Let us focus on the latter comparison.

Figure 5.7(b) represents the percentual gap $(z^N-z^{W2})/z^{W2}$ as a function of *d* values, for the three values of *n* considered in our numerical simulation exercise. We can observe a range of *d* values, which widens as *n* gets higher, in which the Cournot-Nash solution implies an *underfishing* result, relative to the second best welfare benchmark ($z^N<z^{W2}$). In other words, the range of *d* values that implies Cournot-Nash *overfishing* becomes smaller as *n* gets higher.

In the duopoly case (n=1), the *overfishing* gap implies an industry's total effort which is approximately 33% higher, when d=1, than the optimal total effort for the second best planner. With n=3 and d=1, the Cournot-Nash solution implies a total effort which is approximately 6% higher than the second best solution; with n=10 and d=1, the overfishing percentual gap is nearly equivalent to 1% of z^{W2}.

The latter trend of a decreasing (second best) overfishing gap, as *n* gets higher, implies an interesting underlying intuition. As the number of follower firms (which are not under the control of the social planner) gets higher, we obtain an increase in the (*over*)estimation of the Cournot-Nash overfishing that results from using the first best welfare yardstick, instead of using the second best benchmark.

With the first best yardstick, a higher *n* implies a higher Cournot-Nash overfishing. With the second best benchmark, the opposite result occurs. Figures 5.7(c)-(d) help to understand this outcome.

In Figure 5.7(c) we initially observe an increasing positive divergence between z_L^{W2} and z_L^N as *n* gets higher, provided that the sole owner solution is no longer valid. In fact, there exists an intermediate range of *d* values, which widens as *n* gets higher, such that $z_L^{W2} > z_L^N$. Consistent with the latter, in this range of *d* values $z_f^{W2} < z_f^N$. This is the range of *d* values which implies a Cournot-Nash (second best) *underfishing* outcome (Figure 5.7(b)). Hence, the resulting Cournot-Nash underfishing is due to the second best planner's desire to set a higher fishing effort for the more productive firm L, versus z_L^N, in this range of *relatively* low values of the productivity parameter *d*. This range widens as *n* increases due to the triggered higher congestion problem that the social planner aims to avoid or reduce by increasing z_L^{W2}. By contrast with the planner's optimal fishing policy, the Cournot-Nash firm L *monotonically* reduces her optimal effort as *d* and *n* increase, for all *d* values such that $0 < d \leq 1$.

However, starting from a critical value of *d* (whose level depends on the value of *n* in a positive way), the second best welfare planner starts to reduce his own fishing effort as *d* gets higher, with the aim to allow for increasing harvesting from the relatively more productive and more numerous type f firms. In a final stage, which is valid for relatively high values of *d*, that is, relatively close to 1, the welfare planner ends by choosing a full *shut down* policy for his own fishing activity ($z_L^{W2} = 0$). The range of *d* values in which this result is valid depends on the number of rival firms.

In the process when the planner is reducing his own effort z_L^{W2}, because *d* is increasing, there arises a range of *d* values such that $z_L^{W2} < z_L^N$. Consistently, in this range we obtain that $z_f^{W2} > z_f^N$ (Figure 5.7(d)). This is the range of *d* values that implies the Cournot-Nash (second best) *overfishing*. Hence, in this case the overfishing outcome arises due to the planner's preference for a lower z_L, versus the Cournot-Nash z_L^N, when the productivity parameter *d* achieves relatively high levels (getting closer to 1). Notice, however, that the absolute values of the differences $(z_L^{W2}-z_L^N)$ and $(z_f^{W2}-z_f^N)$ become smaller as *n* gets higher. The latter reflects the increasing approximation of the second best welfare solution to a Cournot-Nash equilibrium as *n* increases, given the (final stage) planner's choice such that $z_L^{W2}=0$.

In summary, in the Cournot-Nash fishery we initially obtain a range of intermediate *d* values that imply underfishing with respect to the second best welfare yardstick. This result reflects the planner's desire to increase the harvesting of the more productive firm L along this range of intermediate *d* values. However, as the (relative) productivity parameter of the representative follower firm gets closer to 1, the Cournot-Nash fishery implies second best overfishing. In this case, the planner would prefer a higher fishing effort from the increasingly more productive type f firms, versus the effort chosen by the representative Cournot-Nash firm f.

When we consider the first best welfare yardstick, we obtain (in the Stackelberg and Cournot-Nash fisheries) that an increase in the number of rival firms implies higher overfishing. When we consider the second best benchmark, the opposite result is obtained. The latter reflects the second best planner's decreasing power of control over the industry's total harvesting as more firms enter into the common pool fishery.

Finally, Figure 5.8 represents the positive difference between the industry's total efforts z^S and z^N (as percentage of z^N), for *d* values between 0 and 1 and the three values of *n* considered in our numerical simulation exercises. With the exception of the (common) range of *d* values such that a sole owner solution prevails, we obtain that invariably $z^S>z^N$. Notice also that the simulation results, for $1/6<d<1$, tend to confirm the result (previously derived in section 5.D for $k=d=1$) such that increases in *n* unambiguously reduce the positive gap (z^S-z^N), for n values such that $n\geq2$.

(5.I) Concluding remarks.

This chapter develops three main innovations with respect to the existing literature on static oligopoly harvesting games within deterministic common pool fisheries. First, it develops a consistent analysis of the overfishing ranking that results from comparing Cournot-Nash and Stackelberg equilibria. Second, it develops an explicit comparative analysis for a first best and a second best welfare benchmark. The latter is defined by a social planner who has only partial control upon the industry's total fishing effort and who is endowed with Stackelberg leadership attributes. Third, the commonality of fish stocks is modelled by considering an explicit parameter for a congestion externality effect within each firm's harvesting technology.

We model congestion as a negative externality that reduces (i) each firm's catch (for a given level of the firm's fishing effort) and also (ii) the marginal productivity of each firm's fishing effort. The analysis considers oligopolistic firms subject to price taking behaviour, both in input and output markets.

The traditional modelling of congestion problems within common pool fisheries consists in defining an *aggregate* (industry level) harvesting function subject to decreasing returns in the (aggregate) use of the variable fishing input. Our model, by contrast, individualizes an explicit congestion parameter. This allows the explicit analysis of how different (exogenous) levels of the congestion externality affect the resulting overfishing under different oligopoly equilibria.

Within a duopoly setting, we obtain that exogenous increases in the congestion problem lead to higher oligopoly overfishing. This result is valid both with respect to the first best and the second best welfare benchmarks. For a given level of congestion, we obtain that Stackelberg leadership attributes in hands of a static profit maximizing private firm imply higher overfishing versus the case of a Cournot-Nash fishery. This overfishing ranking is consistent with the results obtained by previous static oligopoly harvesting models (Cornes and Sandler, 1983; Mason, Sandler and Cornes, 1988) where the modelling of a negative parameter of conjectures variations, within oligopoly equilibria of the latter type, intensifies the overfishing that prevails under Nash type (zero) conjectures.

The positive overfishing gap between the Stackelberg and Cournot-Nash fisheries, that is $(z^S - z^N) > 0$ with $z^N > z^{W2} > z^{W1}$, widens as the congestion problem increases (as k gets higher). This is due to the increasing harvesting preemption power that a Stackelberg leader obtains as the congestion problem increases. The harvesting preemption power is due to the first mover advantage that the Stackelberg leader has. This advantage reinforces the incentives to anticipate the harvesting of rival firms that arise from the presence of common property fish stocks. For a range of *relatively* high values of the congestion parameter (k closer to 1), a private Stackelberg leader increases his optimal fishing effort as the congestion rises. In this case, the effect of increasing preemption powers dominates over the effect of a declining marginal productivity of fishing efforts that is also produced by increases in the congestion problem. By contrast, a Cournot-Nash firm invariably reduces her fishing effort as the congestion increases.

The higher industry's total fishing effort that results in the Stackelberg fishery, versus the Cournot-Nash case, is a *robust* result with respect to parametric changes in: (i) the number n of rival firms, (ii) the relative technological size of the congestion externality effect (parameter k), and (iii) the proportional productivity differential d that we model in favour of the leading firm (relative to her followers).

However, we obtain that the positive difference between the Stackelberg and Cournot-Nash industry's total efforts, that is $(z^S - z^N) > 0$, tends to decrease as the number of rival firms increases (for $n \geq 2$). This is due to the reduction in the Stackelberg leader's preemption power over each individual follower firm as more follower firms enter into the fishery. In other words, the larger the industry's size is, in the sense of more numerous firms, the smaller the Stackelberg leader's harvesting preemption effect on each individual follower firm.

We also obtain a decreasing difference $(z^S-z^N)>0$ as the value of parameter *d* (followers' relative marginal productivity) increases. The presence of follower firms with higher harvesting productivity (relative to the leader) increases the industry's total effort both in the Stackelberg and the Cournot-Nash fishery. But the aggregate increase in fishing efforts is smaller in the former case, because the private Stackelberg leader tends to choose a lower fishing effort due to the marginal reduction in his harvesting preemption powers as his rivals become more productive.

The explicit analysis of two alternative welfare yardsticks allows us to derive some interesting generalizations with respect to the prevailing literature on fisheries. We obtain that a *sole owner* solution is not always the socially optimal fishing policy. Full specialization in a single harvesting firm[31], subject to price taking behaviour, has been the standard welfare benchmark within common pool fisheries economics, starting with the classic pioneering papers of Gordon (1954) and Scott (1955), and following later with the classic models of Clark (1980) and Levhari and Mirman (1980). On occasions, the use of the sole owner welfare yardstick has gone beyond methodological clarifying purposes towards its defense on policy grounds (see Charles', 1988, survey paper).

In our discussion the sole owner solution prevails, in the four oligopoly equilibria considered in the analysis, for a range of sufficiently high productivity differentials in favour of one of the oligopolist firms (relatively low values of *d*). In this case the leading (higher productivity) firm is able to fully preempt the harvesting of her rivals. Clark's (1980) discussion presents a duopoly solution on the latter line of thought. In the case of the first best welfare planner, the sole owner solution tends to dominate over other policy options as the congestion problem becomes higher $(k \geq 1)$ and/or the harvesting productivity of the fringe of follower firms becomes lower.

[31] In a more general sense, this implies *unified* management of total harvesting activities.

Our definition of the first best welfare case, as it happens in its standard treatment within the literature on fisheries economics, requires the fulfillment of three strong assumptions: (1) that the social planner has *full* control on the composition and operation of the total harvesting fleet; (2) that the social planner is as well informed as private firms, and (3) that the planner's decision making, monitoring and enforcing processes are all institutionally costless, in the sense that the modelling discussion assigns no explicit additional cost to the functioning of the welfare planner, relative to the private firms' decision making and controlling processes.

Our second best welfare exercise relaxes the previous assumption (1) and illustrates, within a fully deterministic setting, how the explicit consideration of limitations on the welfare planner's powers of control reduces the range of oligopoly harvesting equilibria that can be associated with (constrained) inefficient *overfishing*. Hence, the use of the second best welfare yardstick tends to reduce the magnitude of the overfishing problem, relative to the levels defined by first best considerations.

For instance, the second best welfare solution tends to imply smaller overfishing gaps in the Stackelberg and Cournot-Nash fisheries as the number of follower firms increases, even though the industry's total harvesting tends to monotonically increase with a higher n. The decreasing oligopoly overfishing gaps reflect the lower planner's control over the industry's total harvesting as more firms enter into the common pool fishery. The use of the first best welfare yardstick implies the opposite result: a higher number of operational firms tends to increase the oligopoly overfishing.

Figure 5.1(a). Second best welfare equilibria. (k=n=1)

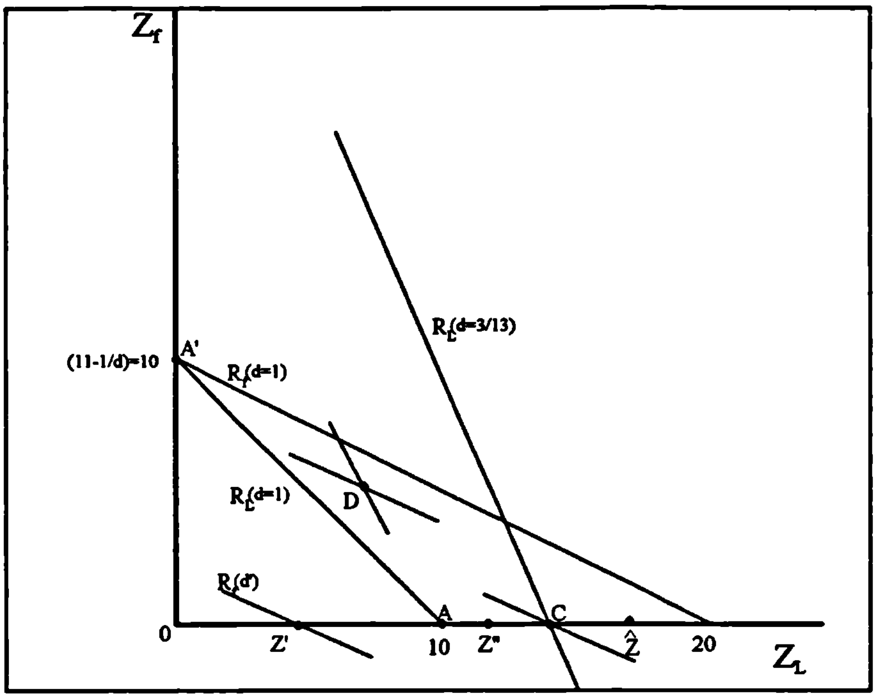


Figure 5.1(b)

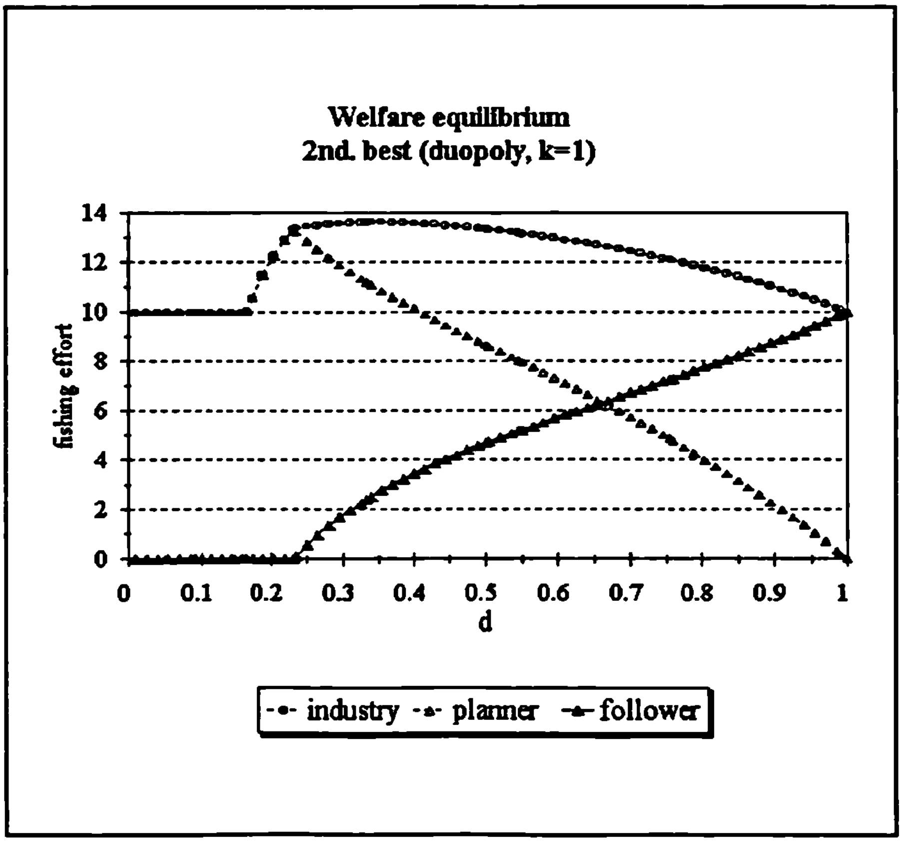


Figure 5.2(a). Stackelberg equilibria. (k=n=1)

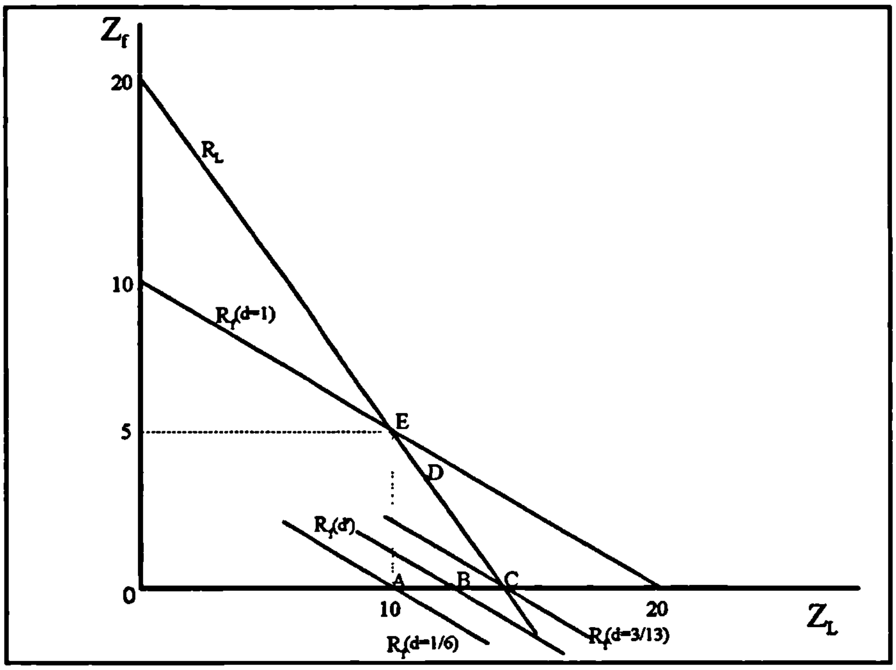


Figure 5.2(b)

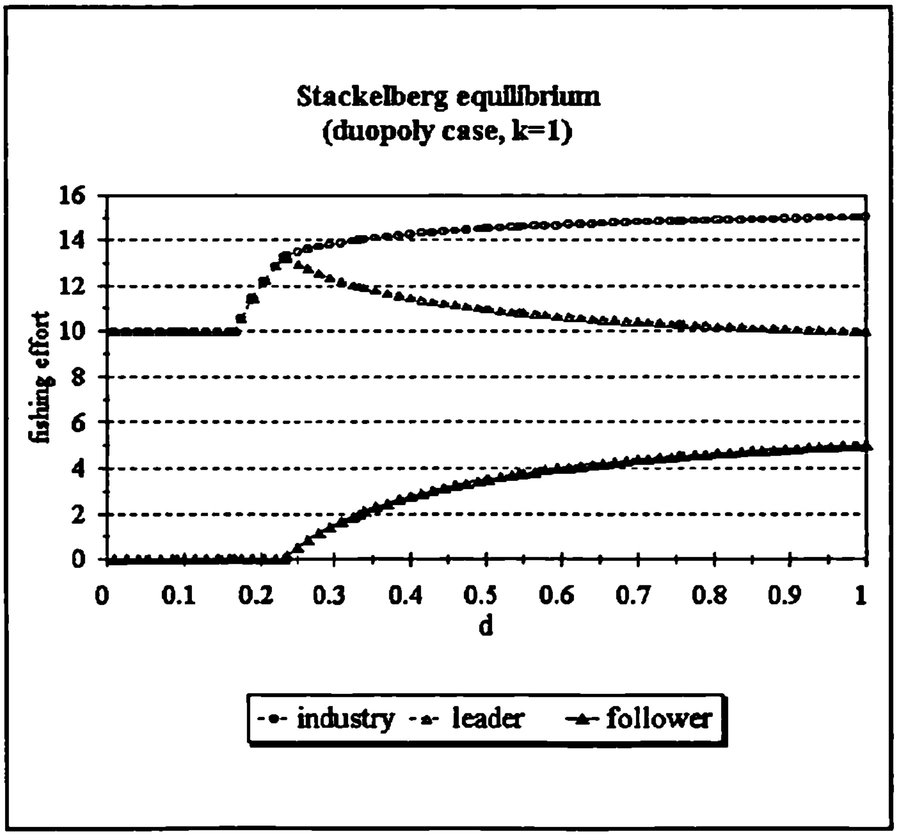


Figure 5.3(a). Cournot-Nash equilibria. (k=n=1)

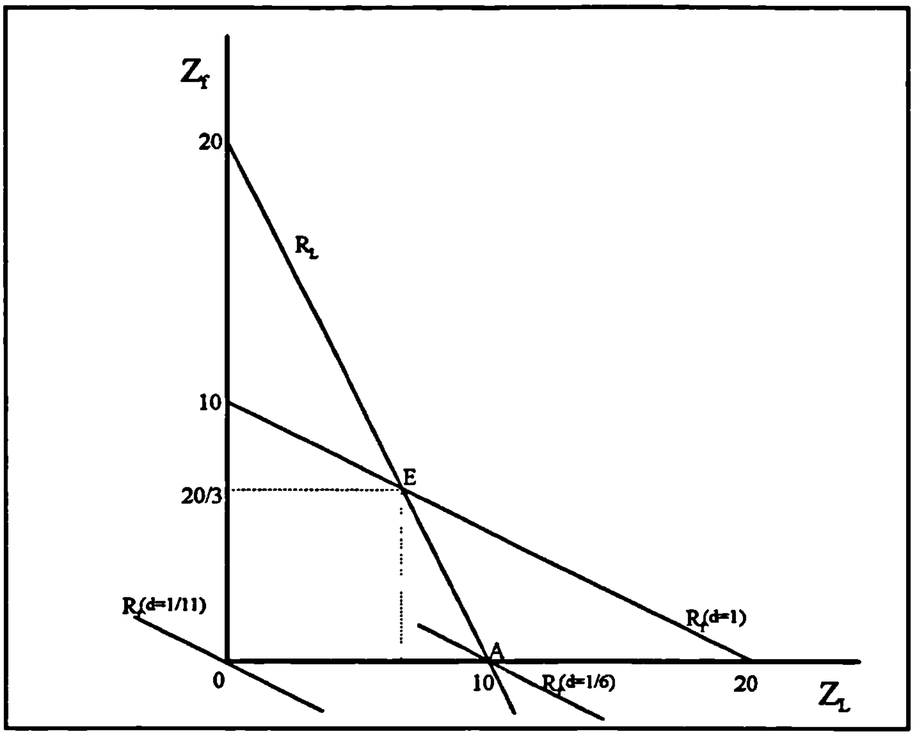


Figure 5.3(b)

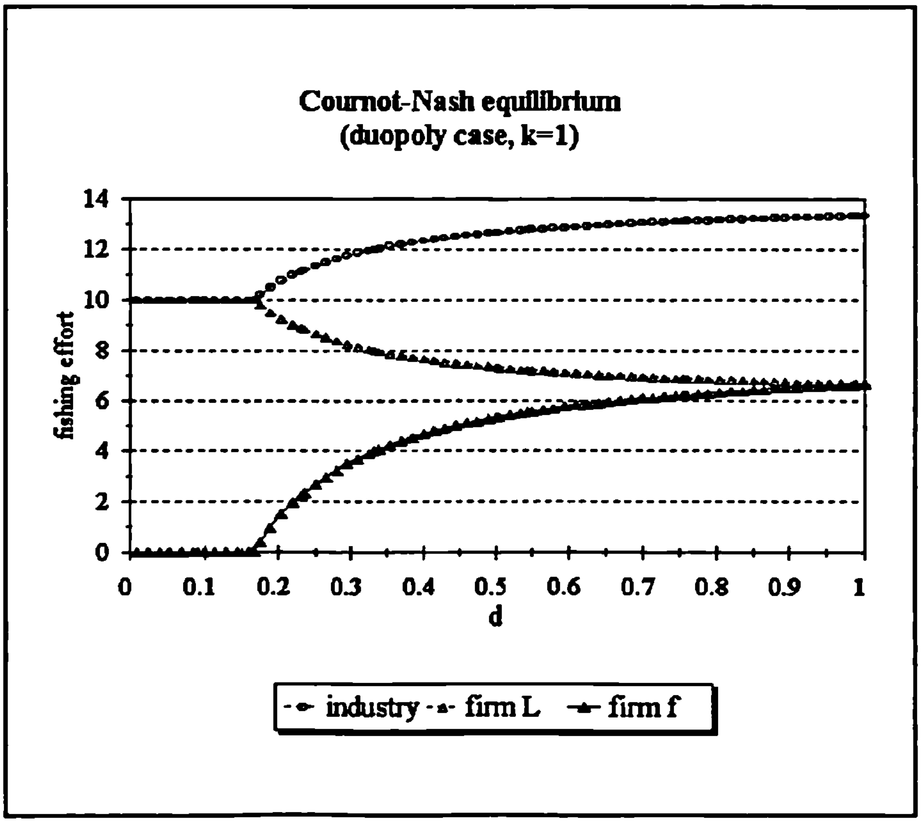


Figure 5.4(a)

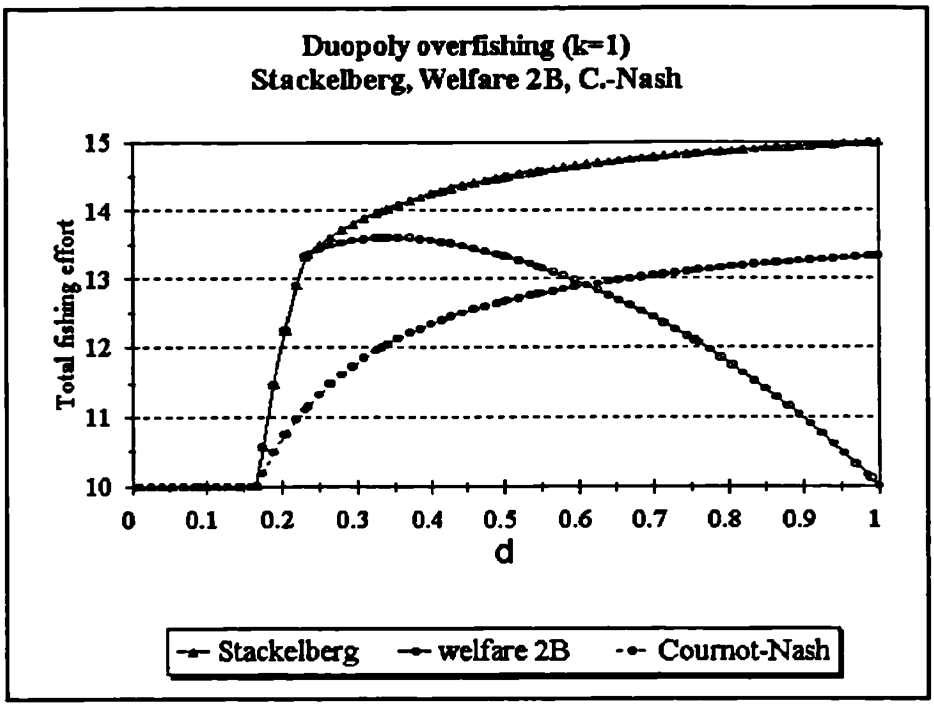


Figure 5.4(b)

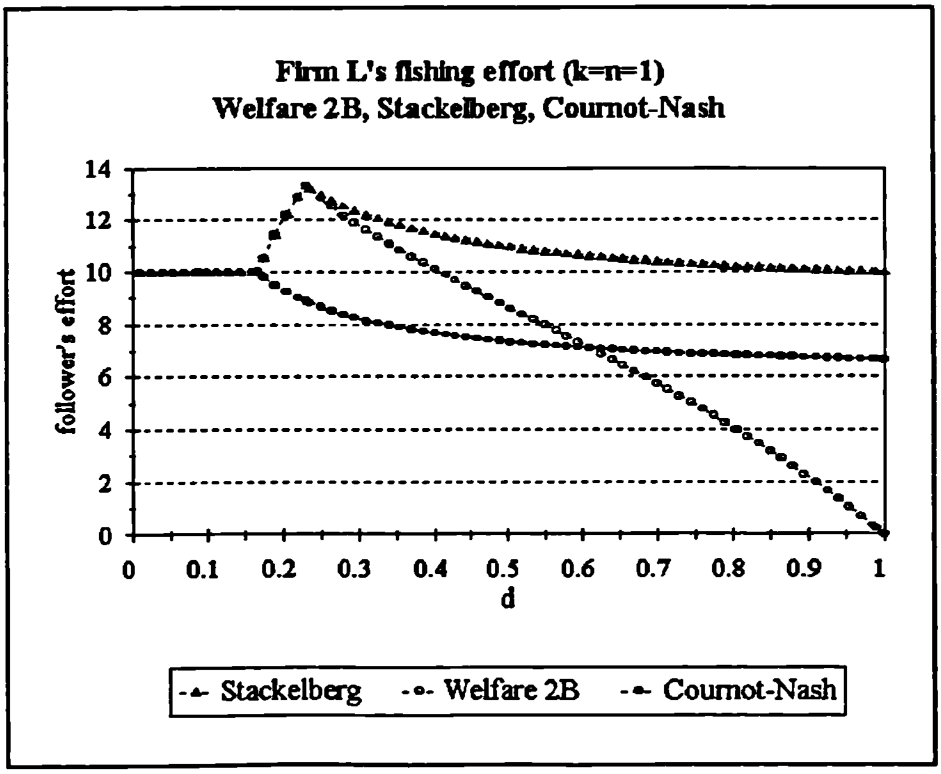


Figure 5.4(c)

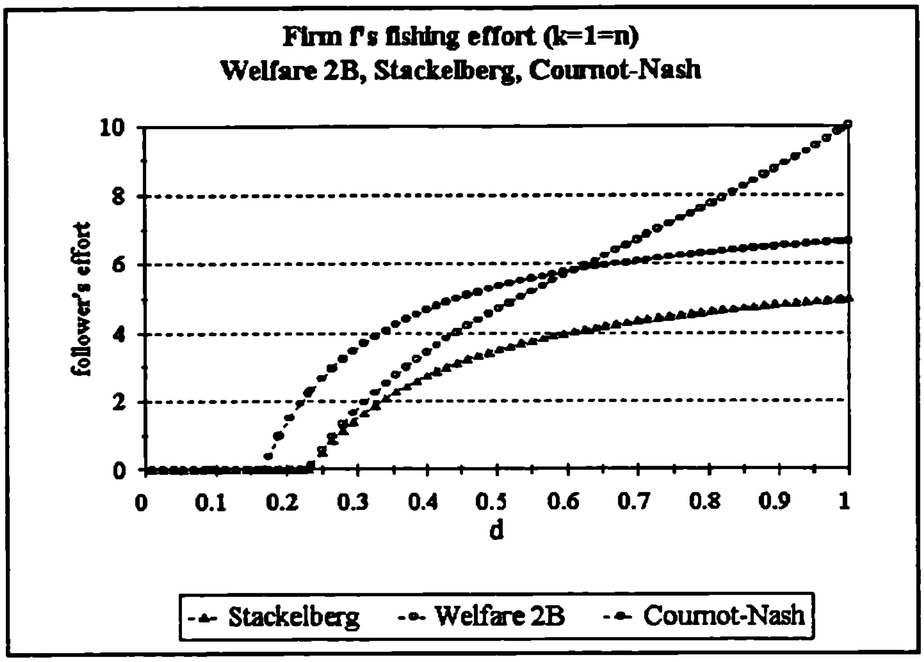


Figure 5.5(a)

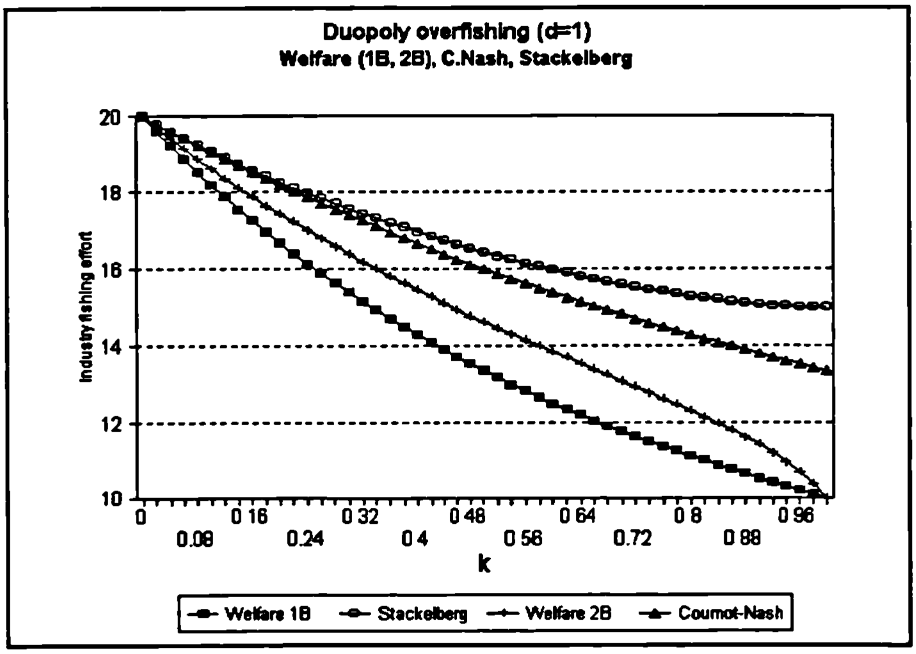


Figure 5.5(b)

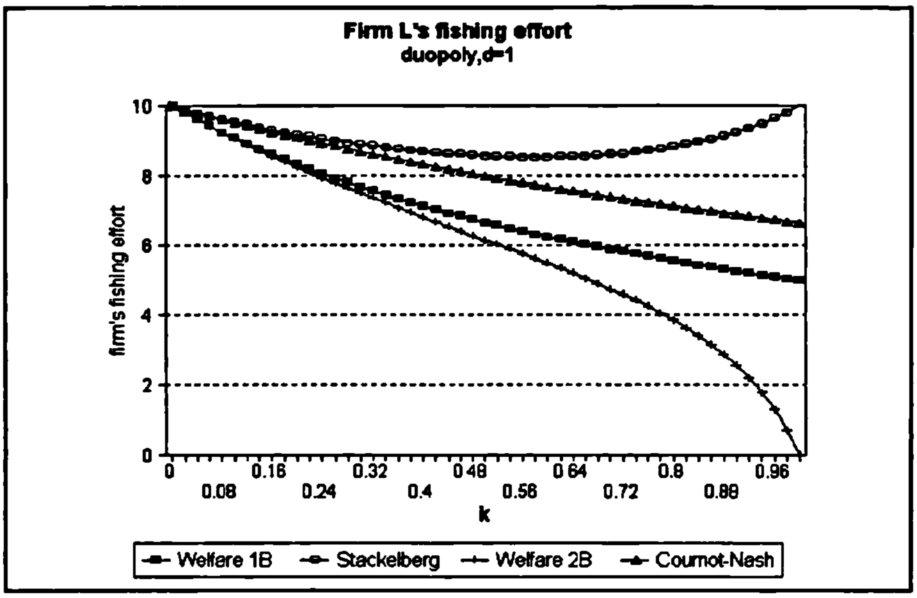


Figure 5.5(c)

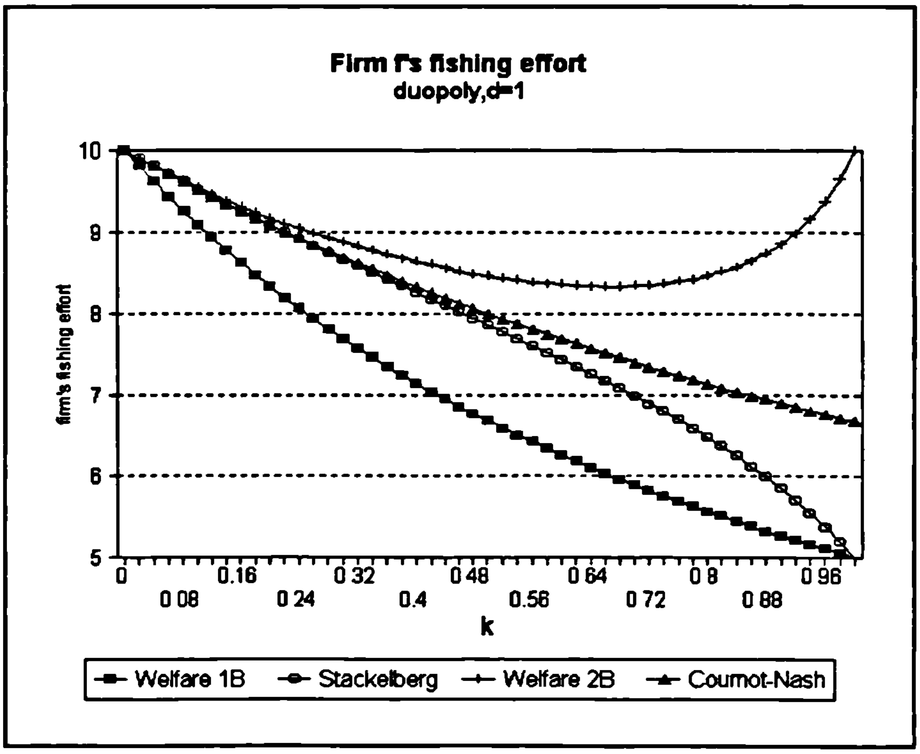


Figure 5.6(a)

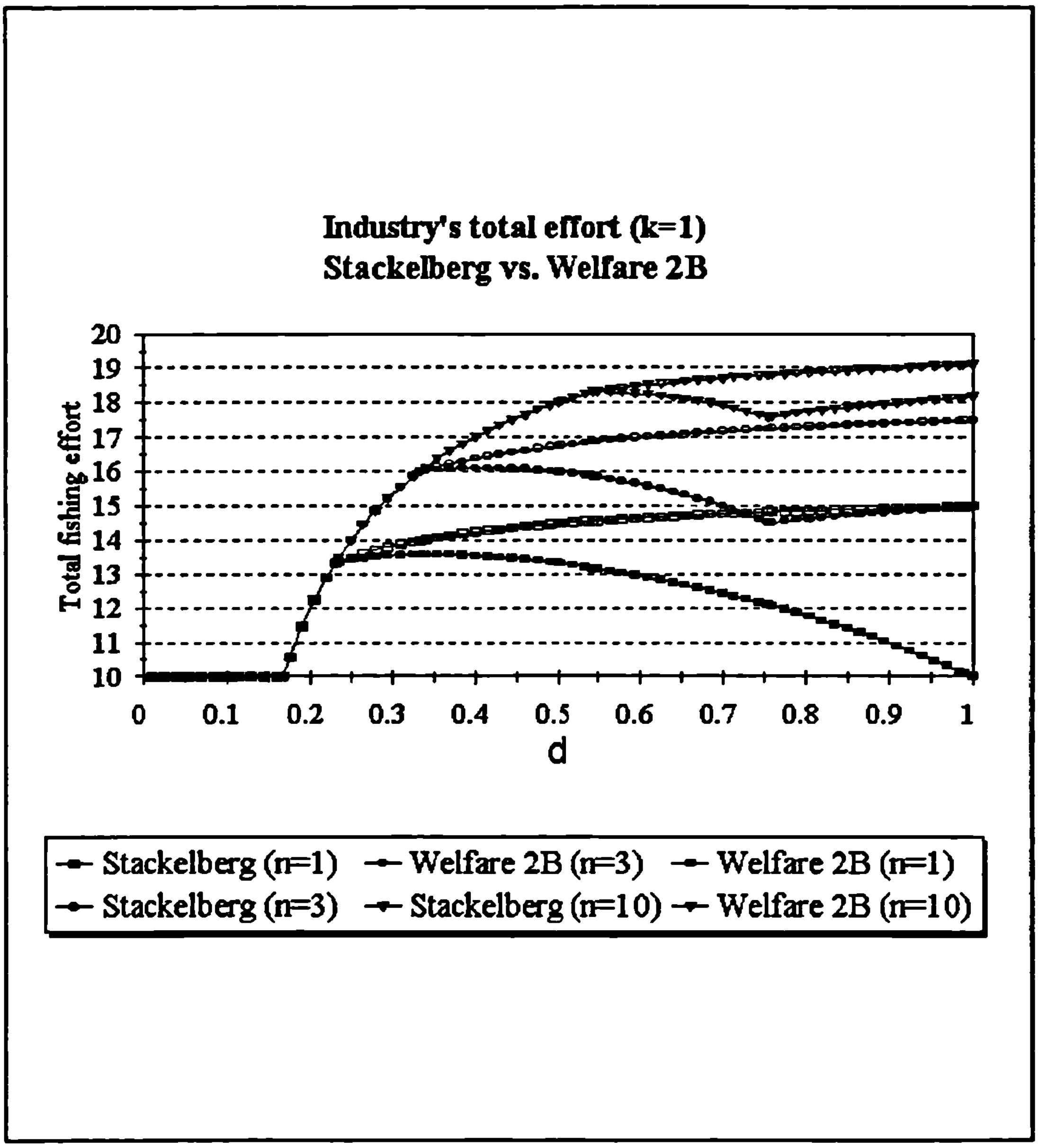
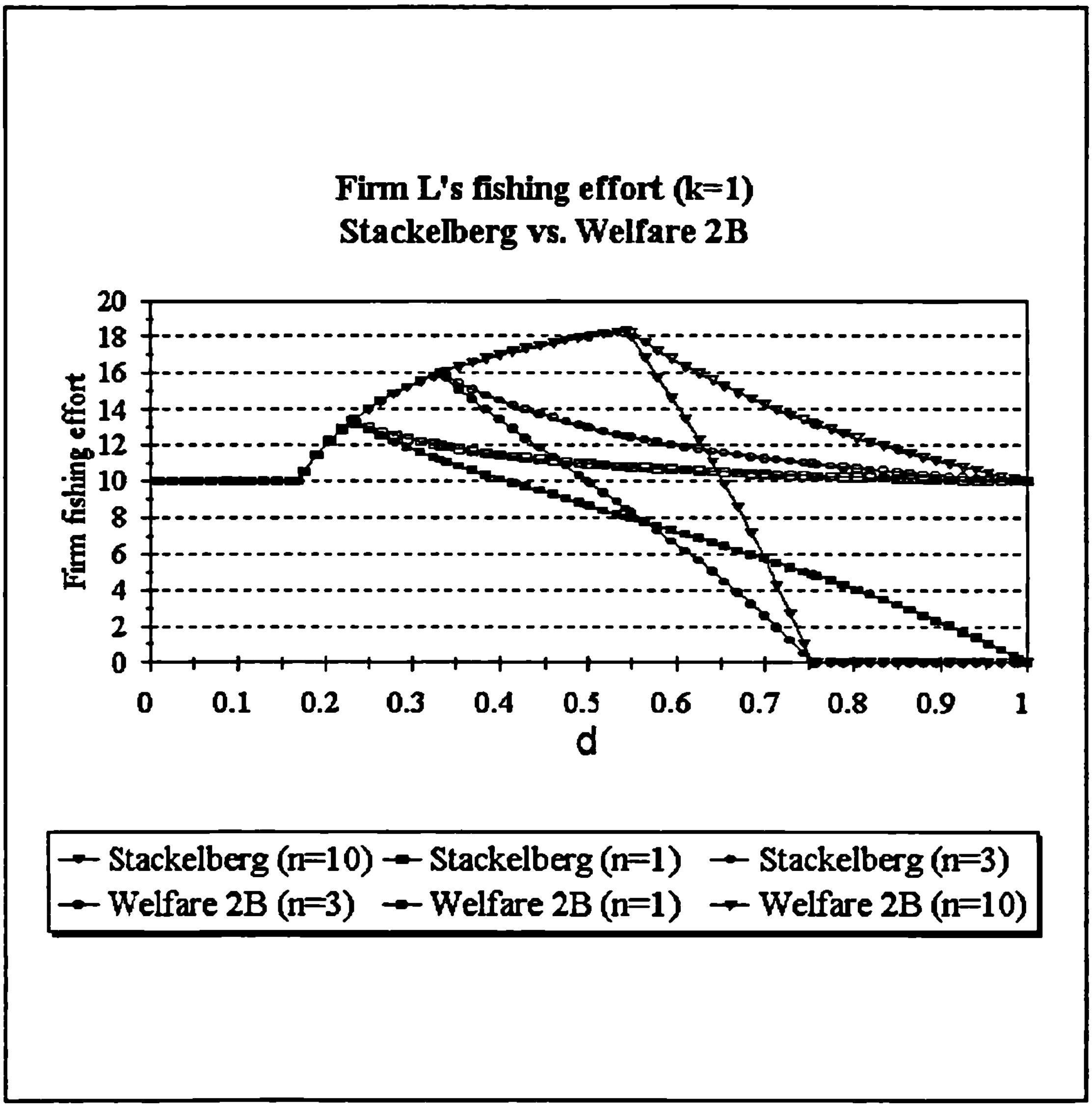

Industry's total effort (k=1)
Stackelberg vs. Welfare 2B
Total fishing effort
20
19
18
17
16
15
14
13
12
11
10
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
d
Stackelberg (n=1)
Welfare 2B (n=3)
Welfare 2B (n=1)
Stackelberg (n=3)
Stackelberg (n=10)
Welfare 2B (n=10)

Figure 5.6(b)



Firm L's fishing effort (k=1)
Stackelberg vs. Welfare 2B
Firm fishing effort
20
18
16
14
12
10
8
6
4
2
0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
d
Stackelberg (n=10)
Stackelberg (n=1)
Stackelberg (n=3)
Welfare 2B (n=3)
Welfare 2B (n=1)
Welfare 2B (n=10)

Figure 5.6(c)

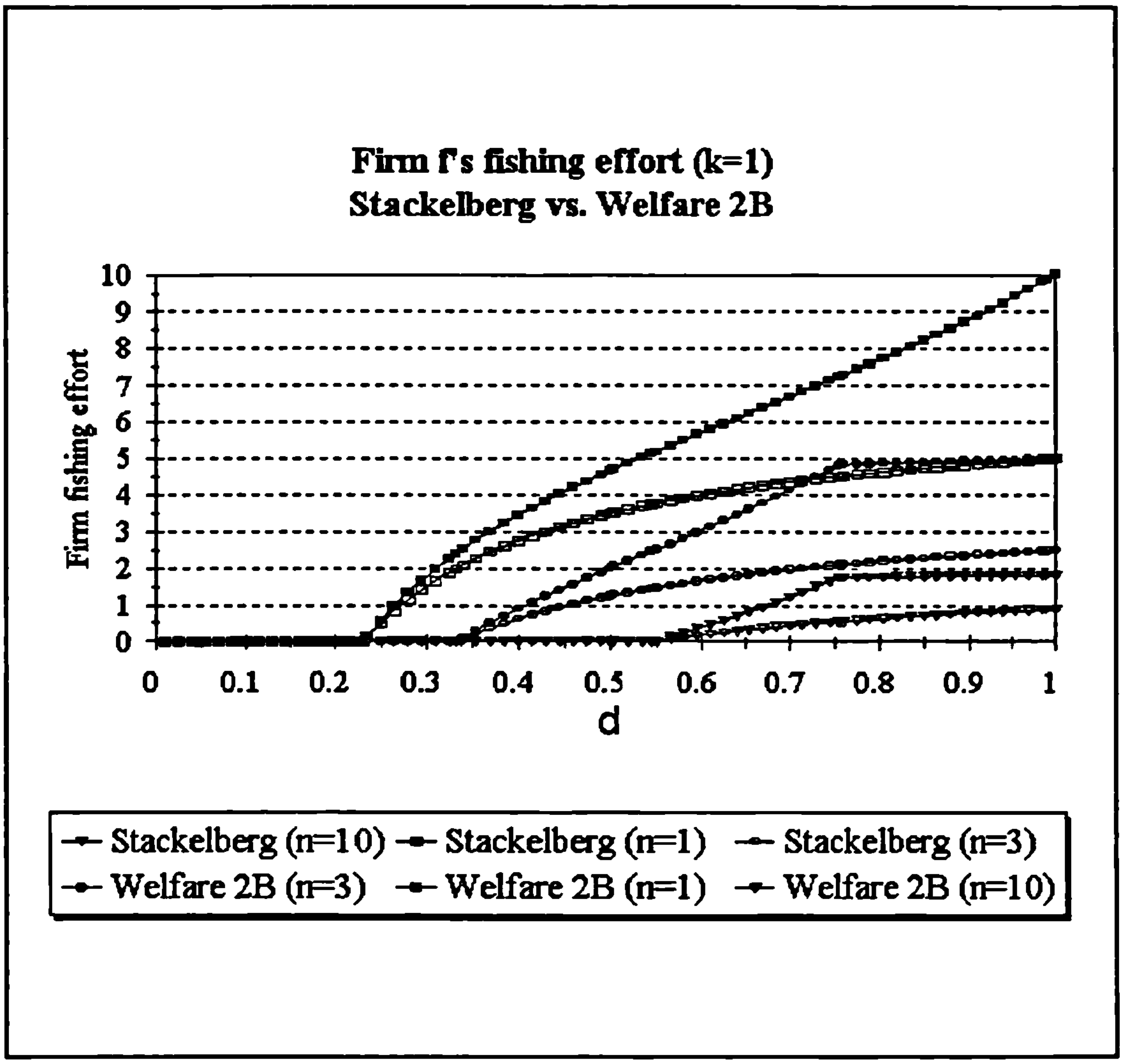

Firm f's fishing effort (k=1)
Stackelberg vs. Welfare 2B
Firm fishing effort
10
9
8
7
6
5
4
3
2
1
0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
d
Stackelberg (n=10)
Stackelberg (n=1)
Stackelberg (n=3)
Welfare 2B (n=3)
Welfare 2B (n=1)
Welfare 2B (n=10)

Figure 5.6(d)

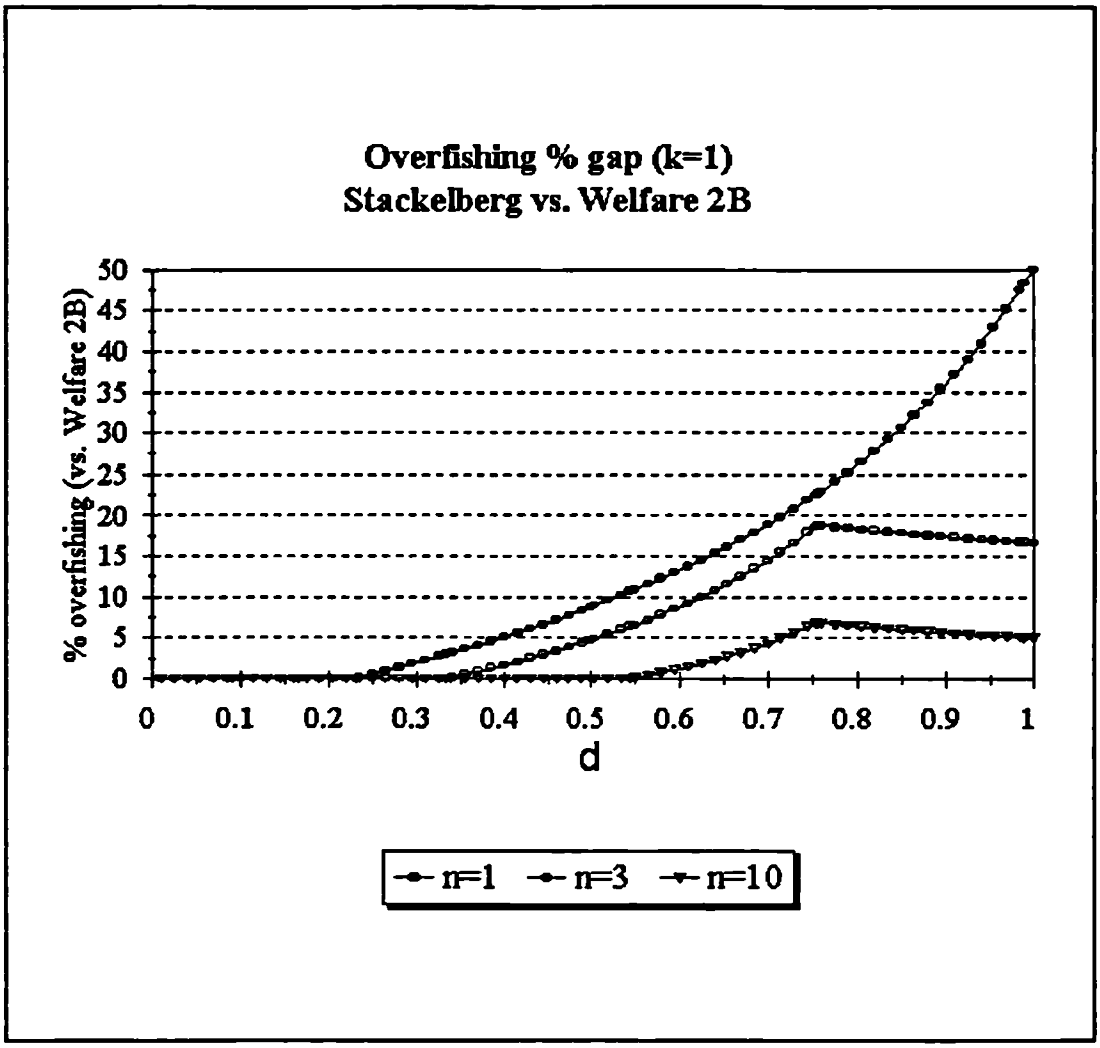

Overfishing % gap (k=1)
Stackelberg vs. Welfare 2B
% overfishing (vs. Welfare 2B)
50
45
40
35
30
25
20
15
10
5
0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
d
n=1
n=3
n=10

Figure 5.7(a)

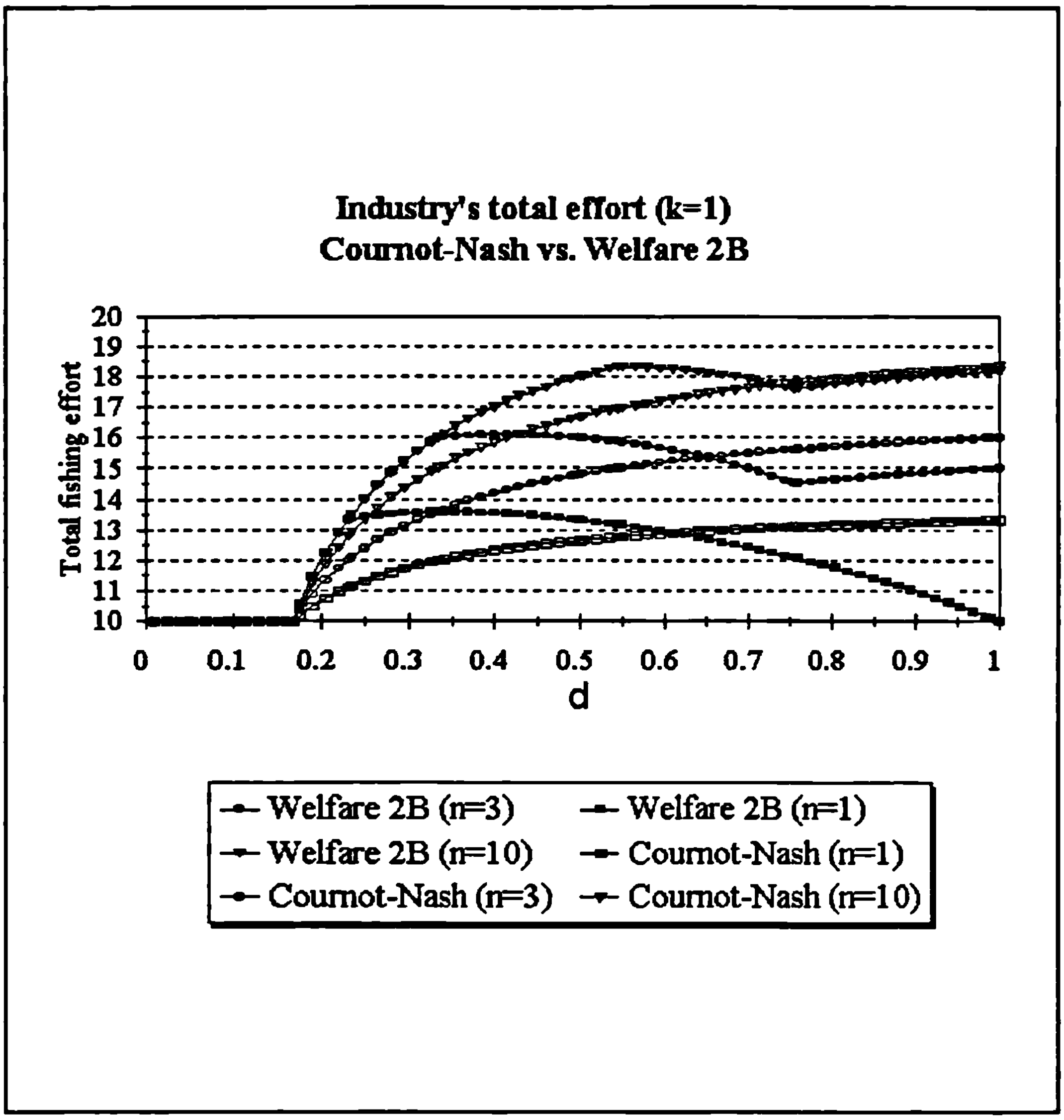

Industry's total effort (k=1)
Cournot-Nash vs. Welfare 2B
Total fishing effort
20
19
18
17
16
15
14
13
12
11
10
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
d
Welfare 2B (n=3)
Welfare 2B (n=1)
Welfare 2B (n=10)
Cournot-Nash (n=1)
Cournot-Nash (n=3)
Cournot-Nash (n=10)

Figure 5.7(b)

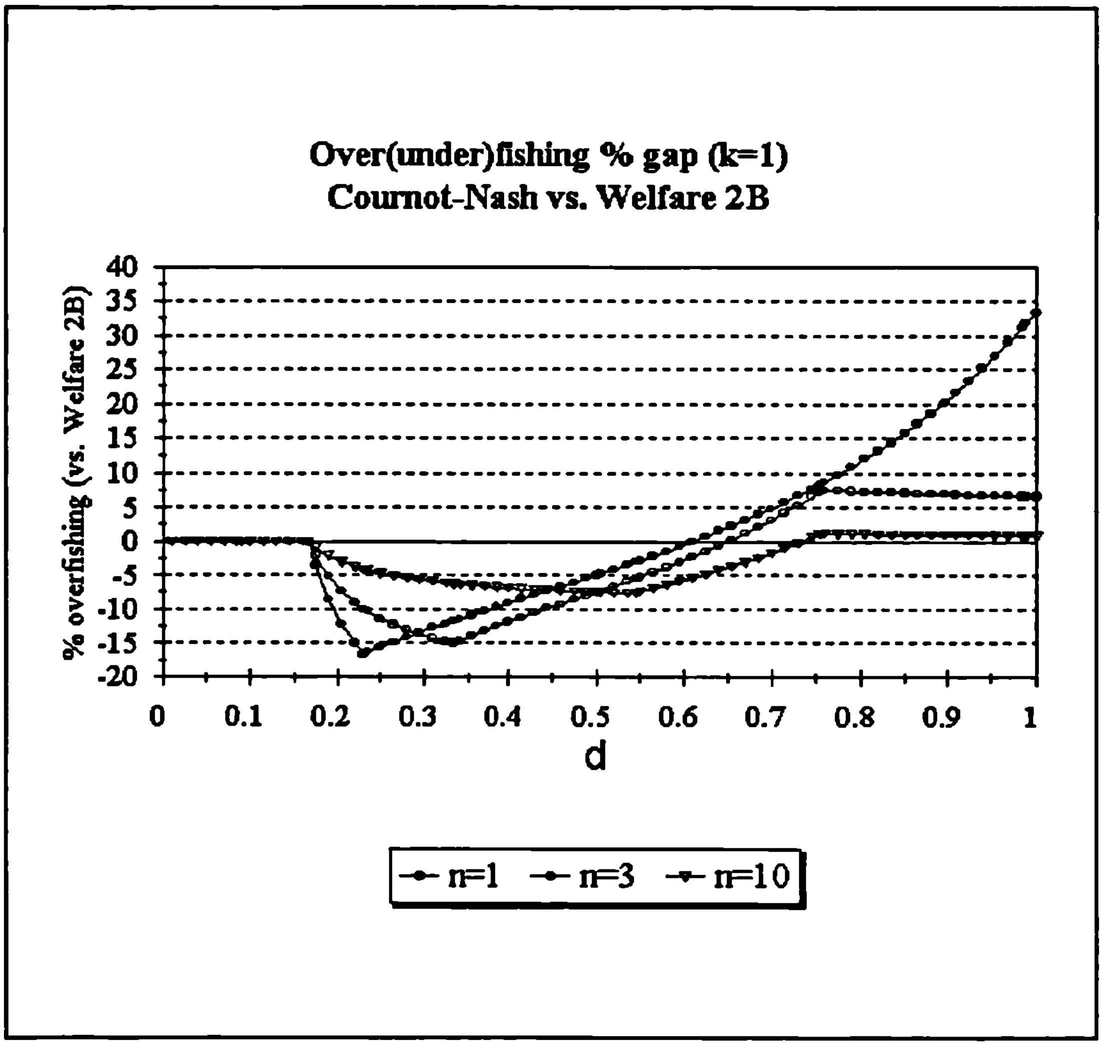

Over(under)fishing % gap (k=1)
Cournot-Nash vs. Welfare 2B
% overfishing (vs. Welfare 2B)
40
35
30
25
20
15
10
5
0
-5
-10
-15
-20
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
d
n=1
n=3
n=10

Figure 5.7(c)

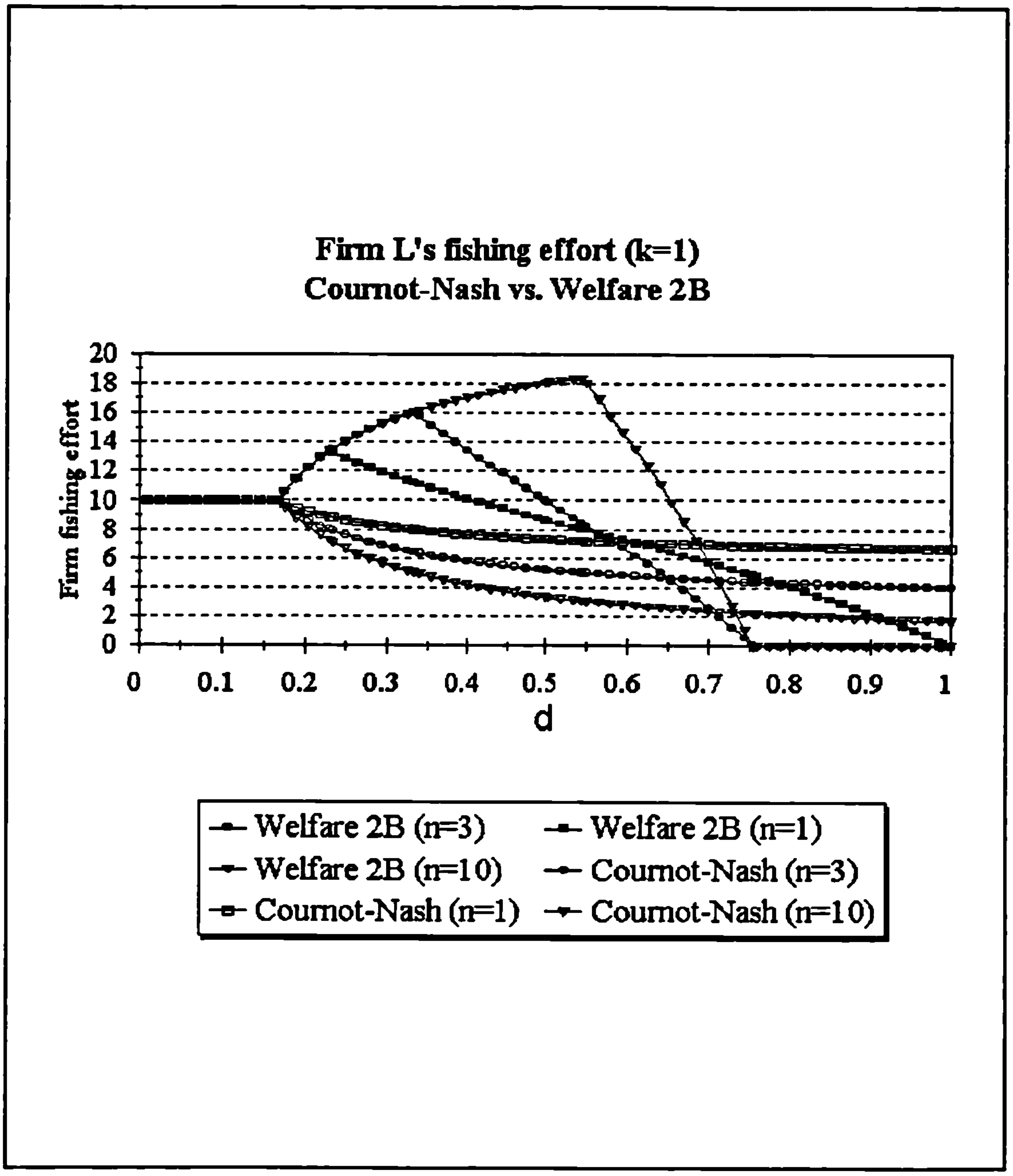

Firm L's fishing effort (k=1)
Cournot-Nash vs. Welfare 2B
Firm fishing effort
20
18
16
14
12
10
8
6
4
2
0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
d
Welfare 2B (n=3)
Welfare 2B (n=1)
Welfare 2B (n=10)
Cournot-Nash (n=3)
Cournot-Nash (n=1)
Cournot-Nash (n=10)

Figure 5.7(d)

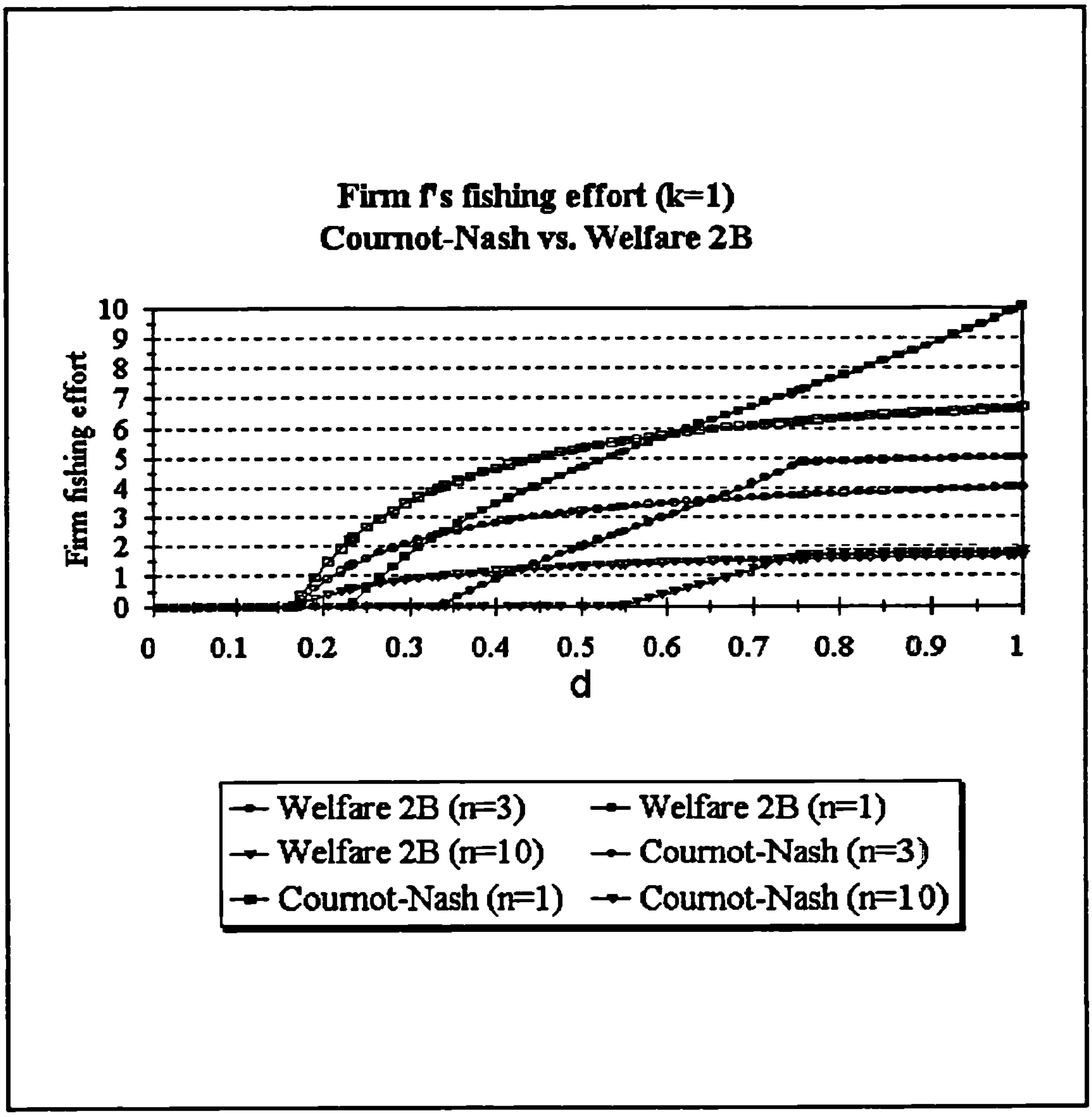
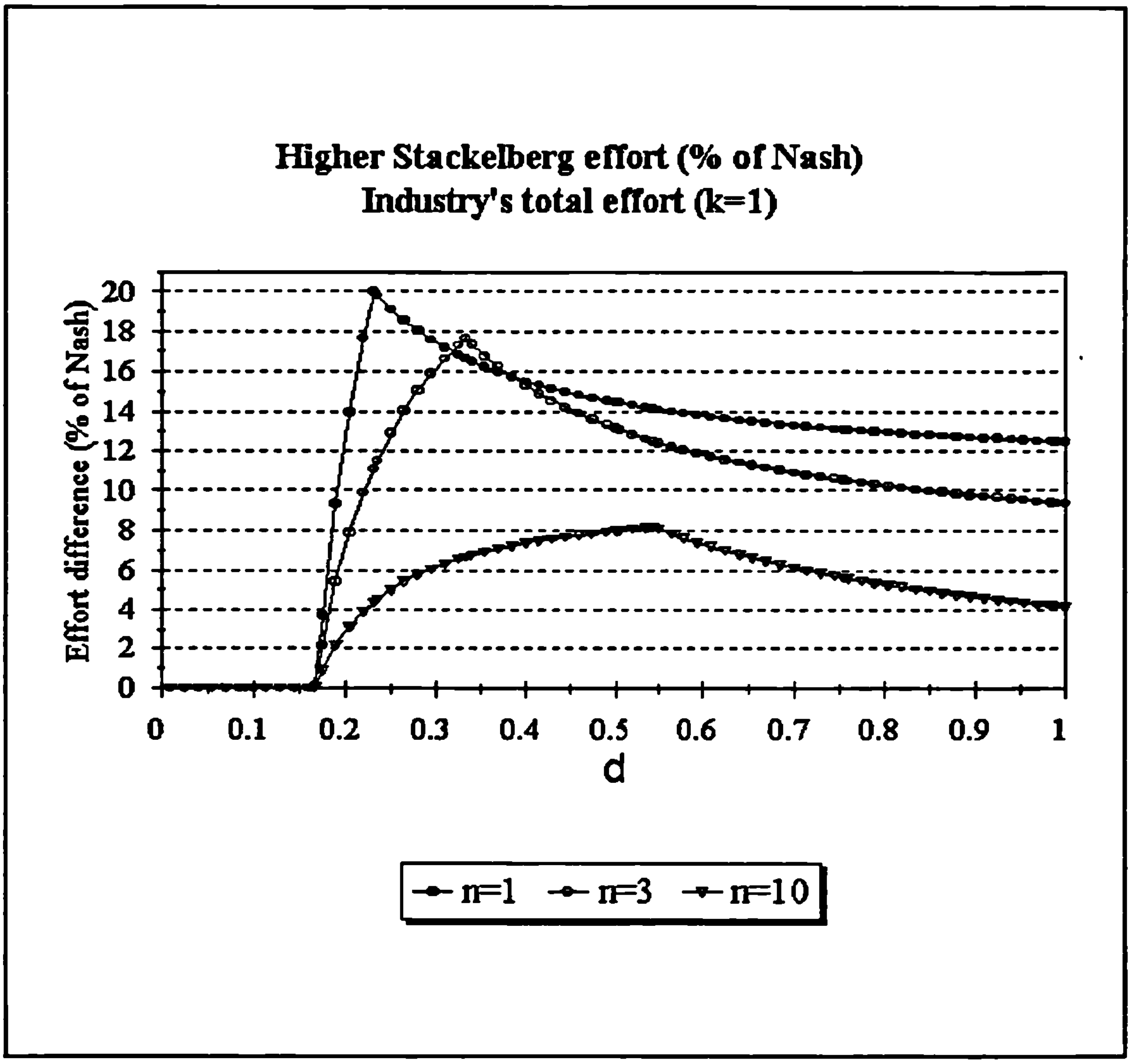

Firm f's fishing effort (k=1)
Cournot-Nash vs. Welfare 2B
Firm fishing effort
10
9
8
7
6
5
4
3
2
1
0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
d
Welfare 2B (n=3)
Welfare 2B (n=1)
Welfare 2B (n=10)
Cournot-Nash (n=3)
Cournot-Nash (n=1)
Cournot-Nash (n=10)

Figure 5.8


Higher Stackelberg effort (% of Nash)
Industry's total effort (k=1)
Effort difference (% of Nash)
20
18
16
14
12
10
8
6
4
2
0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
d
n=1
n=3
n=10

(5.J) Appendices

Appendix 5.1: Proof for Proposition 1 (for $0<d\leq 1$).

Rewrite equations (15) and (18) as:

$$z^S = \frac{1}{2\beta}\left[\alpha\left[\frac{2n+1}{n+1}\right] - \frac{w}{p}\left[1+\frac{n}{(n+1)d}\right]\right] \equiv \frac{1}{2\beta}[C] \tag{A1}$$

$$z^N = \frac{1}{2\beta}\left[\alpha\frac{2(n+1)}{n+2} - \frac{w}{p}\frac{2}{d}\frac{(n+d)}{n+2}\right] \equiv \frac{1}{2\beta}[D] \tag{A2}$$

To prove that invariably $z^S > z^N$, we need to show that invariably C > D. From (A.1) we can rewrite C as:

$$C=\frac{(2n+1)}{2(n+1)}\frac{(n+2)}{(n+1)}\left[\alpha\frac{2(n+1)}{n+2} - \frac{2w}{pd}\frac{(n+d)}{(n+2)}\left[\frac{(n+1)d+n}{(n+d)}\right]\left[\frac{n+1}{2n+1}\right]\right] \tag{A3}$$

(i) Denote by E the term outside big brackets in (A3). We know that:

$$E = \frac{2n+1}{2(n+1)}\frac{n+2}{n+1} = \frac{[(2n+1)\ /\ (n+1)]}{[2(n+1)\ /\ (n+2)]}$$

and

$$\frac{2n+1}{n+1} = \frac{2(n+1)}{n+2} + \frac{n}{(n+1)(n+2)}$$

Therefore, we know that E $>$ 1 for any $n>0$.

(ii) Denote the following expression by F:

$$F \equiv \left[\frac{(n+1)d \ + \ n}{n+d}\right] \left[\frac{n+1}{2n+1}\right]$$

If $F \leq 1$, then invariably $C > D$, given that (i) is true. If $F \leq 1$, then the following relationship is also true:

$$F \leq 1 \Leftrightarrow \frac{d+n+nd}{d+n} \leq \frac{n+1+n}{n+1}$$

The validity of this inequality requires that $nd(n+1) \leq n(d+n)$. This requires that $n^2d \leq n^2$. Given that $d \leq 1$, this inequality is always true. Therefore $F \leq 1$ is always true and, hence, invariably $z^S > z^N$ when $0 < d \leq 1$

Appendix 5.2

Duopoly Equilibria
(k = 1, n = 1, 0 < d < 1)

	STACKELBERG	COURNOT-NASH	WELFARE 1st - best	WELFARE 2nd - best
$z^{industry}$	$\frac{3}{2}\frac{1}{2\beta}\left(\alpha - \frac{w}{p}\frac{(2+(1/d))}{3}\right)$	$\frac{4}{3}\frac{1}{2\beta}\left(\alpha - \frac{w}{p}\frac{(1+(1/d))}{2}\right)$	$\frac{1}{2\beta}\left(\alpha - \frac{w}{p}\right)$	$\frac{1}{2\beta}\left[1 + \frac{1-d}{2-d}\right]\left[\alpha - \frac{w}{pd}\left(\frac{1}{3-2d}\right)\right]$
z_L	$\frac{1}{2\beta}\left(\alpha - \frac{w}{p}\frac{(2d-1)}{d}\right)$	$\frac{2}{3}\frac{1}{2\beta}\left(\alpha - \frac{w}{p}\frac{(2d-1)}{d}\right)$	$\frac{1}{2\beta}\left(\alpha - \frac{w}{p}\right)$	$\frac{1}{2\beta}\left[\frac{2(1-d)}{2-d}\right]\left[\alpha - \frac{w}{pd}\frac{(2d-1)}{2(1-d)}\right]$
z_f	$\frac{1}{2\beta}\left(\frac{\alpha}{2} - \frac{w}{pd}\left(\frac{1}{2}+(1-d)\right)\right)$	$\frac{4}{3}\frac{1}{2\beta}\left(\frac{\alpha}{2} - \frac{w}{pd}\frac{(1+(1-d))}{2}\right)$	0	$\frac{1}{2\beta}\left(\alpha - \frac{w}{pd}\right) - \left(\frac{z_L}{2}\right)$

Appendix 5.3: Duopoly equilibria with d=1 and 0≤k≤1

(5.3.a) First best welfare solution.

The planner's problem consists in maximizing the representative firm i's current profits, that is:

$$\max_{z_i} W=p(\alpha z_i-(\beta+\gamma)z_i^2)-wz_i \tag{C.1}$$

The first order condition $(\partial w/\partial z_i)=0$ implies:

$$z_i=\frac{1}{2(\beta+\gamma)}\left[\alpha-w/p\right] \tag{C.2}$$

Hence the first best welfare total effort $z^{wl}=2z_i=\left[\alpha-w/p\right]/\beta(1+k)$, with $k=\gamma/\beta$. With the parametric assumptions in section (5.G), $z^{wl}(k=0)=20$,whereas $z^{wl}(k=1)=10$.

(5.3.b) Second best welfare solution

Now the planner's problem consists in:

$$\max_{z_L} W=p(h_L+h_f)-w(z_L+z_f) \tag{C.3}$$

with

$$h_L=\alpha z_L-\beta z_L^2-\gamma z_L z_f \tag{C.4}$$

$$h_f=\alpha z_f-\beta z_f^2-\gamma z_L z_f$$

The first order condition $\partial W/\partial z_L=0$ implies:

$$\alpha\left[1+\frac{\partial z_f}{\partial z_L}\right]-2\beta z_L-2\gamma\left[z_f+z_L\frac{\partial z_f}{\partial z_L}\right]-2\beta z_f\frac{\partial z_f}{\partial z_L}=\frac{w}{p}\left[1+\frac{\partial z_f}{\partial z_L}\right] \tag{C.5}$$

Firm f is a Cournot-Nash follower. Hence, using equation (7) and $n=1$,

$$\frac{\partial z_f}{\partial z_L}=-\frac{\gamma}{2\beta}=-k/2.$$

Introducing equation (7) into (C.5), we obtain:

$$z_L^{w2} = \frac{(\alpha - w/p)(1-k)}{2\beta - 3\gamma^2/2\beta} \tag{C.6}$$

The equilibrium value of the follower's fishing effort z_f can be obtained by introducing (C.6) into equation (7) in section (5.C).

Note that if $k=1$, and $d=n=1$, solution (C.6) corresponds to the leader's optimal effort summarized in Table 5.4.

(5.3.c) Stackelberg duopoly

We obtain the effort solutions z_L^s and z_f^s by simply introducing the parametric assumptions $d=n=1$ into equations (10) and (11-12). Doing so, we obtain:

$$z_L^s = \frac{C(2-k)}{2-k^2}, \qquad \text{with } C = \frac{1}{2\beta}\left[\alpha - \frac{w}{p}\right] \tag{C.7}$$

and

$$z_f^s = z_L^s\left[1 - \frac{k^2}{2(2-k)}\right] \tag{C.8}$$

(5.3.d) Cournot-Nash duopoly

Given that $d=1$, duopolists $(i=1,2)$ are symmetric firms. The representative firm i's optimization problem consists in:

$$\max_{z_i} \quad V^i = p\left(\alpha z_i - \beta z_i - \gamma z_i z_j\right) - w z_i, \quad j \neq i \tag{C.9}$$

The first order condition $\partial V^i / \partial z_i = 0$ implies:

$$z_i = \frac{1}{2\beta}\left(\alpha - w/p\right) - \frac{\gamma}{2\beta} z_j \tag{C.10}$$

Given that $d=1$, in equilibrium $z_i = z_j$. Hence (C.10) implies:

$$z_i^N = \frac{(\alpha - w/p)}{2\beta(1 + k/2)}$$

Appendix 5.4: Second best welfare equilibria with $k=1$, $0 \le d \le 1$ and $n \ge 1$

The planner's optimization problem is, given the presence of n symmetric type f firms:

$$\max_{z_L} W = p\Big[\alpha z_L - \beta z_L^2 - \beta z_L(nz_f) + nd\big(\alpha z_f - \beta z_f^2 - \beta z_f(z_L + (n-1)z_f)\big)\Big] - w(z_L + nz_f) \quad \text{(D.1)}$$

subject to the fact that the representative firm f chooses z_f in a Cournot-Nash fashion; that is, using equation (7) and the fact that $k=1$, the representative follower's optimal fishing effort is given by:

$$z_f = \frac{\alpha - w/pd}{\beta(n+1)} - \frac{z_L}{n+1} \quad \text{(D.2)}$$

and hence $\partial z_f / \partial z_L = -1/(n+1)$. Solving for the first order condition $\partial W / \partial z_L = 0$ and using the information in (D.2), we obtain:

$$z_L = \frac{(K\alpha - w/p)}{\beta(K+1)} - \frac{n(K+d)}{(K+1)} z_f, \qquad \text{with } K = n(1-d) + 1 \quad \text{(D.3)}$$

By combining (D.2) and (D.3) we can obtain the second best welfare solution $\{z_L^{W2},\ z_f^{W2}\}$, with the industry fishing effort equal to $z^{W2} = z_L^{W2} + n z_f^{W2}$.

Let us consider the case when $k = 1 = d$ and, hence, $K = 1$. In this case, by combining (D.2) and (D.3) we obtain that $z_L = [(\alpha - w/p)/2\beta](1-n)$. This implies that $z_L \le 0$ as long as $n \ge 1$ and the representative firm f is active (the latter implies that $(\alpha - w/p)/2\beta > 0$). Therefore, as long as $z_f > 0$, the second best welfare planner's optimal fishing policy will be to set $z_L = 0$

Let us now derive the second best welfare equilibria for n=3 and n=10, leaving the effort solutions as a function of parameter d. We consider the parameter values which are valid for the numerical solution exercise, that is, $\alpha = 11$, $\beta = 1/2$, $(w/p) = 1$.

(5.4.a) n=3

In this case the follower's equilibrium effort conditional on the leader's effort is :

$$R_f(d) \equiv z_f = \frac{(11 - 1/d)}{2} - \frac{z_L}{4} \tag{D.2'}$$

whereas the planner's optimal effort conditional on z_f is given by (see equation (D.3)):

$$R_L(d) \equiv z_L = \frac{(43 - 33d)2}{(5 - 3d)} - \frac{6(2 - d)}{(5 - 3d)} z_f \tag{D.3'}$$

Equations (D.2')-(D.3') allow to obtain the second best welfare equilibria as a function of parameter d. Solving by numerical simulation the system (D.2') - (D.3'), for $0 < d \leq 1$ we verify that:

(i) for $0 < d \leq 1/6$, $z_f(d) = 0$ requires a $z_L(d)$ value such that $0 \leq z_L(d) \leq 10$. This means that for $0 < d \leq 1/6$, the second best planner can choose the best fishing policy which is consistent with the presence of no rivals; that is, the planner sets $z_L^{W2} = 10$ and, hence, the representative follows firm chooses $z_f^{W2} = 0$.

(ii) for $1/6 < d \leq 1/3$, we initially obtain equilibria such that $z_f \leq 0$ and $z_L > 0$. The result $z_f < 0$ implies that $z_f = 0$. This also implies that in this range of d values $\partial z_f / \partial z_L = 0$. As explained in section (5.F), this means that the best policy for the planner is to set z_L such that $R_f(d) \equiv z_f(z_L, d) = 0$. Hence $z_L^{W2} = 2(11 - 1/d)$ and $z_f^{W2} = 0$.

(iii) for $1/3<d<0.7557$, the equilibrium implies that $z_L^{W2}>0$ and $z_f^{W2}>0$. In this case $z_L=(34-66d+12/d)/(4-3d)$ and z_f is given by equation (D.2').

(iv) for $0.7557\leq d\leq 1$, the equilibrium implies $z_L\leq 0$ and $z_f>0$. This implies that $z_L^{W2}=0$ and $z_f>0$ such that $R_f(d)\equiv\ z_f(z_L=0,d)>0$. Hence $z_f=(11-1/d)/2$.

(5.4.b) n=10

In this case:

$$R_f(d)\equiv\quad z_f=2(1-\frac{1}{11d})-\frac{z_L}{11} \tag{D.2''}$$

and

$$R_L(d)\equiv\quad z_L=\frac{120-110d}{(6-5d)}-\frac{5(11-9d)}{(6-5d)}z_f \tag{D.3''}$$

Solving by numerical simulation the system (D.2'')-(D.3''), for $0<d\leq 1$, we verify that :

(i) for $0<d\leq 1/6$, $z_L^{W2}=10$ and $z_f^{W2}=0$ (same reasons as in the case with n=3).

(ii) for $1/6<d\leq 6/11$, the equilibria are such that $z_f\leq 0$ and $z_L>0$. This implies that in this range of d values, $z_f^{W2}=0$. As previously explained, this means that the planner's optimal policy is to set $z_L^{W2}=2(11-1/d)$. (set $z_f=0$ in equation (D.2''))

(iii) for $6/11<d<0.754$, the equilibrium implies that $z_L^{W2}>0$ and $z_f^{W2}>0$. In this case, $z_L=20(1-11d+5.5d)/(11-10d)$ and z_f is given by (D.2'').

(iv) for $0.754\leq d\leq 1$, the equilibrium implies $z_L\leq 0$ and $z_f>0$. As in the case with n=3, this result implies that in this range of d values $z_L^{W2}=0$ and $z_f^{W2}=2(1-1/11d)$.

Appendix 5.5: Cournot-Nash equilibria with $k=1$, $0<d\leq 1$ and $n\geq 1$.

In this case the representative firm f's equilibrium value of z_f conditional on z_L is given by equation (D.2). Firm L also behaves in a Cournot-Nash fashion. Hence, her optimal effort z_L, conditional on the value of z_f, is equal to:

$$z_L = \frac{\alpha-(w/p)}{2\beta} - \frac{nz_f}{2} \qquad \text{(E.1)}$$

By combining (D.2) and (E.1) we obtain the Cournot-Nash equilibrium $\{z_f^N, z_L^N\}$ with $z^N=(z_L^N+nz_f^N)$. Let us derive the corresponding equilibria, as a function of d, for $n=3$ and $n=10$ (with $\alpha=11$, $\beta=0.5$ and $w/p=1$).

(5.5.a) n=3.

In this case $R_f(d)$ is given by equation (D.2'), whereas $R_L(d)$ implies $z_L= 10- 3/2z_f$. Solving this system by numerical simulation, for $0<d\leq 1$, we verify that:

(i) for $0<d\leq 1/6$, the higher productivity firm L can behave as a sole owner; hence, she chooses $z_L^N=10$, whereas $z_f^N=0$. (same reasoning as in previous cases).

(ii) for $1/6<d\leq 1$, both z_L and z_f are positive in equilibrium (note that $R_f(1/6)\Rightarrow z_f(z_L=10)=0$), with $z_L^N(d)= 14/5 + 6/(5d)$ and $z_f^N(d)$ is given by (D.2').

(5.5.b) n=10.

In this case $R_f(d)$ is given by equation (D.2''), whereas $R_L(d)$ implies $z_L= 10\text{-}5z_f$. Solving this system by numerical simulation, for $0<d\leq 1$, we verify that:

(i) for $0<d\leq 1/6$, we again obtain $z_L^N=10$ and $z_f^N=0$.

(ii) for $1/6<d\leq 1$, again both z_L and z_f are positive in equilibrium, with $z_L^N=10/(6d)$ and $z_f^N(d)$ is given by (D.2'').

Appendix 5.6: Stackelberg equilibria with $k=1$, $0<d\leq 1$ and $n\geq 1$.

The representative firm f's optimal effort z_f conditional on the observed value of z_L is given by (D.2). The leader's equilibrium effort z_L conditional on the value of z_f is obtained by combining equations (7) and (9), the latter implying:

$$z_L = \frac{(n+1)}{(n+2)}\left[\frac{\alpha-(w/p)}{\beta} - nz_f\right] \qquad \text{(F.1)}$$

Let us derive the Stackelberg equilibria for $n=3$ and $n=10$, for values of d such that $0<d\leq 1$, assuming that $\alpha=11$, $\beta=0.5$ and $w/p=1$.

(5.6.a) n=3

Again $R_f(d)$ is given by (D.2'), whereas (F.1) in this case implies $z_L=16-(12/5)z_f$. Solving this system by numerical simulation, for $0<d\leq 1$, we verify that:

(i) for $0<d\leq 1/6$, we again obtain $z_L^S=10$ and $z_f^S=0$ (same reasoning as before).

(ii) for $1/6<d\leq 1/3$, the equilibrium implies that $z_f\leq 0$ and $z_L>0$. The result $z_f<0$ implies $z_f=0$. As explained in section (5.F), this implies that in this range of d values the best policy for the Stackelberg leader is to set z_L such that $R_f(d)\equiv z_f(z_L,d)=0$. Hence $z_L^S=2(11-(1/d))$ and $z_f^S=0$.

(iii) for $1/3<d\leq 1$, both z_L and z_f are positive in equilibrium, with $z_L^S=7+(3/d)$ and $z_f^S(d)$ is given by (D.2').

(5.6.b) n=10.

$R_f(d)$ is given by (D.2''), whereas equation (F.1) now implies $z_L=110/6-(55/6)z_f$. Solving this system by numerical simulation, we verify that:

(i) for $0<d\leq 1/6$, we again obtain $z_L^S=10$ and $z_f^S=0$.

(ii) for $1/6<d\leq 6/11$, the equilibrium implies that $z_f\leq 0$ and $z_L>0$. The result $z_f<0$ implies $z_f=0$. Hence, in this range of d values the best policy for the Stackelberg leader is to set z_L such that $R_f(d)\equiv z_f(z_L,d)=0$. Hence $z_L^S=2(11-(1/d))$ and $z_f^S=0$.

(iii) for $6/11<d\leq 1$, both z_L and z_f are positive in equilibrium, with $z_L^S=10/d$ and $z_f^S(d)$ is given by (D.2'') and, hence, equal to $z_{f\cdot}=2(1-6/(11d))$.

CHAPTER 6
OVERFISHING IN A DYNAMIC SETTING

(6.A) Introduction.

In this chapter we focus our attention on the effect that firms' current harvesting has on the law of motion for fish stocks. The common property of fish stocks implies that firms' current harvesting generates a *dynamic* or *stock* externality. This corresponds to the impact that rival firms' current harvesting has on future fish stock and, through that, on other decision makers' future payoffs. This will be the source of overfishing outcomes in this chapter. The magnitude of the overfishing result will depend on the specific equilibrium concept that is considered for the oligopoly harvesting game. We compare the overfishing ranking between Stackelberg and Cournot-Nash solutions. First best and second best welfare benchmarks are used to assess overfishing.

This chapter models the overfishing problem as the result of *endogenous* differences between the marginal social scarcity value of the common pool fish stock and the marginal value assigned to it by non-cooperative oligopolistic firms. We discuss the meaning of *myopic* decision rules, making a distinction between the concepts of static profit optimizing rules and Pareto inefficient harvesting myopia. In the literature on fishery models, the distinction is not always clear.

In each of the harvesting equilibria studied, we examine the impact of increasing the number of rival firms upon the fishing incentives faced by the different types of oligopolistic harvesting firms. The formal analysis of this issue is a contribution to the literature on dynamic oligopolistic harvesting games. Previous dynamic models have basically studied *duopoly* harvesting competition games (Clark, 1980; Levhari and Mirman, 1980; Dockner et al., 1989).

For the case of a common pool fish stock harvested by $N>1$ dynamic profit optimizing Cournot-Nash firms, we show that an increasing number of rival firms amplifies the overfishing problem *only* for a limited range of number of firms. This result appears counter intuitive when contrasted with the traditional *open access* result that stems from popular *static* discussions of overfishing (Gordon, 1954; Dasgupta and Heal, 1979; Cornes, Mason and Sandler, 1986).

In our *dynamic* deterministic setting, firms face two effects which help dynamic profit optimizing firms to increasingly internalize the higher scarcity of the common pool stock as more firms enter the fishery: on the one hand, *declining* biological growth returns for relatively overdepleted stock levels, due to our use of a strictly concave biological growth function. This effect arises from the function which introduces dynamics into our discussion. On the other hand, an increasingly lower marginal productivity of fishing efforts as the fish stock falls due to a larger number of firms. This effect results from our use of a harvesting technology subject to positive but declining marginal productivity of fish stock levels. This effect is normally absent from fishery models due to the commonly used Schaefer harvesting technology which is linear in stock levels.

We also examine the overfishing consequences of increasing the number of rival firms in a multi-firm harvesting model where there is only one dynamic optimizing firm competing with numerous static profit optimizing Cournot-Nash rivals. We analyse the harvesting equilibria that result from modelling the single dynamic optimizing agent as a: (i) profit maximizer Stackelberg leader, (ii) another (profit optimizing) Cournot-Nash firm and (iii) a second best welfare planner who aims at maximizing the discounted value of the *industry*'s intertemporal profits. This exercise aims to illustrate the possibility of a dominant firm that behaves as a dynamic optimizing agent, despite competing with fully myopic rivals, and who may also have Stackelberg leadership attributes. The motivation lies on the empirical evidence described in chapters 3 and 4 suggesting the presence of industrial concentration at important marine industrial fisheries.

We show that in the three previous cases (i, ii, and iii) the dynamic optimizing agent decides to leave the fishery for a sufficiently large (finite) number of fully myopic rivals. This occurs due to the increasingly lower marginal productivity of fishing efforts owing to depleted stock levels. Static profit optimizing firms react more slowly to these productivity penalties and thereby contribute to the possibility that the fish population becomes extinguished.

In our setting Stackelberg leadership does not yield any private advantage (versus the case of passive Cournot-Nash conjectures) because static optimizing followers' optimal efforts are independent of rivals' current fishing effort. This result stems from the absence of congestion static externalities (via pecuniary or technological effects) in our harvesting model and also from the *static* profit optimizing character of followers' decision making. The presence of a second best welfare planner improves only *transitorily* the overfishing problem, relative to the Stackelberg equilibrium: the second best welfare planner, with limited control on the industry's total harvesting fleet, also decides to leave the fishery for a sufficiently large number of static profit optimizing non-cooperative firms.

We complement the analysis with a final exercise where we allow for the possibility that the single dynamic optimizing Stackelberg leader has productivity advantages over the static profit optimizing followers. The main result is that the leading firm behaves as a *counteracting* factor in fishing effort patterns induced by productivity changes among the followers: if followers' productivity increases, the leading firm reduces his fishing effort and vice versa.

This chapter is organized as follows. Sections (6.B) and (6.C) discuss and review background material. Section (6.B) discusses four important building blocks in a dynamic model for a common property and multi-firm fishery. Section (6.C) reviews four models that have some similarities to our discussion in this chapter. We do so in order to highlight the contribution of our analysis.

Sections (6.D) and (6.E) describe and develop our basic modelling framework. Section (6.D) defines the basic setting for analysis. Section (6.E) develops our first best optimality benchmark in which the welfare planner controls all firms. Section (6.F) solves for the case of a fishery with N identical *dynamic profit optimizing* Cournot-Nash harvesting firms. Subsection (6.F.1) discusses the concept of *myopic* harvesting, while subsection (6.F.2) examines the effect of an increasing number of rival firms on the degree of inefficient Nash myopia.

Sections (6.G) and (6.H) examine an oligopolistic fishery with a single dynamic profit optimizing Stackelberg leader and $n \geq 1$ fully myopic Nash followers. This Stackelberg equilibrium is compared with: a Cournot-Nash fishery where all firms behave as fully myopic agents (section 6.G.1); a Cournot-Nash fishery which also has a *single* dynamic profit optimizing (Nash) firm (section 6.G.3); a Cournot-Nash fishery where *all* firms are dynamic profit optimizing agents (section 6.G.2); and finally, with a fishery where the single dynamic optimizing agent is a second best welfare planner that controls only one firm, among other $n \geq 1$ non-cooperative Nash harvesters, and aims to maximize the industry's total discounted intertemporal profits (section 6.G.4). Section (6.H) generalizes to a Stackelberg leader with productivity advantages over its followers. Section (6.I) offers concluding remarks. The appendices in section (6.J) contain some technical material.

(6.B) Basic building blocks.

This section describes four key features in the dynamic modelling of an oligopolistic harvesting industry that exploits a common pool fish stock. We compare our assumptions about them with those in previous models in the literature on dynamic harvesting fisheries.

(6.B.1) Strategic (oligopolistic) interactions.

During the 1960s and 1970s, models of overfishing gradually developed *dynamic* aspects. Crutchfield and Zellner (1962) and Plourde (1970) were pioneering papers. Refinements on cost and production structures followed. In this vintage we find Smith (1968, 1970), Quirk and Smith (1970) and Brown (1974).

The idea that open access, common property and decentralized harvesting with static optimizing (myopic) agents would overexploit fish stocks was common to all of them. The *assumption* that fishermen will not consider the resource dynamics as a binding constraint is crucial in their proofs. None of these models offer an endogenous explanation for myopic harvesting. This feature will be modelled in this chapter.

In the above papers strategic considerations were neither discussed nor mentioned as factors affecting harvesting actions. In this chapter, by contrast, we consider strategic interactions, in the sense of oligopolistic harvesting competition, to be at the centre of the commonality problem. As in the rest of the literature, we take it for granted that cooperative harvesting strategies are not feasible because of high monitoring costs.

As in chapter 5, we restrict the analysis to a closed entry fishery. The number of firms is given exogenously. This approach follows Clark's (1980) pioneer work on a non-cooperative Cournot-Nash *duopolistic* harvesting game. Levhari and Mirman's (1980) classic paper follows a similar development, though also developing a brief section on a Stackelberg duopoly solution.

In these two seminal papers each duopolist considers the resource dynamics as a binding constraint. However, none of these models offer an endogenous modelling of the scarcity values assigned by dynamic profit maximizing harvesting firms to the remaining fish stock. This chapter, by contrast, obtains analytical solutions for these scarcity values, under Cournot-Nash and Stackelberg equilibria.

Comparing the oligopoly solutions with an explicit welfare benchmark, we obtain an endogenous explanation for harvesting myopia.

By considering the case of multi-firm harvesting fisheries subject to closed entry, we are also able to analyse how an increasing number of rival firms affects the fishing incentives of different types of harvesting firms (with different strategic conjectures or static versus dynamic optimizing harvesting rules). Sections (6.F.2) and (6.G) examine this issue.

(6.B.2) Sources of oligopolistic interaction.

In models discussing extraction problems for common pool resources, it is frequent to find strategic interactions that stem from the combined effect of (i) pecuniary externalities arising from firms endowed with price setting powers[1] and (ii) technological externalities arising from the commonality feature. In fishery models, Dockner et al. (1989), Kamien, Levhari and Mirman (1985), Mason, Sandler and Cornes (1988) and Cornes, Mason and Sandler (1986) are some examples that combine both effects, the former two within a dynamic setting and the latter two within static frameworks (see Table 6.1).

This chapter focuses on strategic interactions generated by the commonality issue. We assume that harvesters are price takers in input and output markets. Think, for instance, of an exporting fishing industry that takes demand prices as given and likewise assume that harvesting firms face a horizontal supply curve of fishing effort units.

Commonality of fish stocks accounts for the fact that interactions among firms lead to technological externalities. The most common externality in fishery models

[1] In fact, conventional oligopoly models focus on pecuniary externalities.

is a *stock* or *dynamic* externality[2]: the impact that rivals' current harvesting has on the future fish stock and, through that, on the decision maker's future payoffs. This chapter focuses on firms' oligopolistic interactions that stem from the technological externality associated with the so-called *stock* externality effect.

(6.B.3) Closed-loop versus open-loop extraction strategies.

The outcomes from strategic interactions are directly dependent on the strategy spaces of the players. These include, for instance, players' information endowments, possibilities for commitment, and number of interactions. In the case of dynamic problems, an important dimension of the strategy space is the relation between choice (control) and state variables.

Closed-loop strategies refer to cases where the decision maker has access to information on current and past states. Therefore, control variables can be a function of state variables. When there is information only on the current state, the strategy is called a *feedback* rule. *Open-loop* strategies only consider information on the initial states. Consequently, they are chosen as functions of time and independently from additional state information (Basar and Olsder, 1982).

In strategic settings, closed-loop and open-loop strategies do not only differ in terms of information structures. They also imply different assumptions on the players' ability to make credible commitments on strategy time paths. A closed-loop is a *decision rule* strategy: the decision maker chooses a rule relating the control to the state variables. Its credibility depends on whether or not it is a self-enforcing rule. By contrast, an open-loop strategy presupposes that a credible commitment is possible over the entire planning horizon (Reinganum and Stokey, 1985).

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[2] A few fishery models, e.g., Smith (1968) and Brown (1974), include congestion (static) externalities within dynamic frameworks, although none of these models consider congestion problems within strategic (oligopolistic) settings. The usual characterization of congestion problems assumes decreasing returns for fishing effort at the industry level (Table 6.1). A similar procedure, although within pure static grounds, is resorted to in Dasgupta and Heal (1979) and the sequence of their own papers which Mason, Sandler and Cornes (1988) refer to.

Models discussing strategic extraction of exhaustible common pools have shown the importance of open-loop versus closed-loop strategies. These models display a tendency to overextraction when *closed*-loop strategies are considered, if non-cooperative solutions are contrasted with welfare yardsticks such as those mentioned in chapters 4 and 5. Eswaran and Lewis (1984) is a Cournot-Nash example. Within the framework of fishery models, (Cournot-Nash) closed-loop strategies leading to overfishing are considered in Levhari and Mirman (1980), Clark (1980) and Clemhout and Wan (1985b, 1986).

Conversely, Kemp and Long (1980), Weinstein and Zeckhauser (1975) and Chiarella et al. (1984) are models where *open-loop* (Nash) extraction strategies can lead to Pareto efficient outcomes. It has been argued that this result arises, partly, from the implicit commitment abilities that players enjoy in open-loop strategies (Eswaran and Lewis, 1984; Mohr, 1988; Reinganum and Stokey, 1985; Thomas, 1992).

Mohr (1988) and Thomas (1992) further extend this line of thought. Mohr relaxes assumptions in previous models where the *duration* of the game was exogenous by resorting to a free-end-point problem and proves an overextraction outcome when Nash open-loop strategies prevail. He argues this is equivalent to weakening the players' ability to commit. On the other hand, Thomas further expands the players' strategy space, thereby enabling them to obtain ex-post cooperative outcomes by allowing for extraction strategies with full memory over past actions. Full memory makes punishment strategies feasible (credible) under certain conditions and hence it acts as a substitute to open-loop commitments in the promotion of more (ex post) cooperative outcomes.

The second intuition as to why closed-loop strategies tend to produce less cooperative outcomes derives from the strategic *preemptive* incentives that state-dependent extraction strategies bring to bear (Eswaran and Lewis, 1984). An increase in firm i's extraction can preempt state-dependent rivals' extraction, for example, if i enjoys cost advantages or moves first. Even simultaneous symmetric Nash players have incentives to preempt each other, when they exploit a common pool, given their conjectures on rivals' passive reactions.

Our models in this chapter consider closed-loop strategies. They will be self enforcing and dynamically consistent rules for Cournot-Nash players as well as for the Stackelberg leader. This differs from the open-loop strategies that the leader and followers follow in Dockner et al. (1989) and Plourde and Yeung (1989). Open-loop strategies impose strong assumptions on players' ability to make commitments. For fishery industries, frequently subject to random supply shocks, such a presumption can lead to misleading conclusions.

(6.B.4) Harvesting technology.

When fishery models consider an explicit harvesting function, they usually assume *linearity* with respect to fishing effort (variable input) and fish stocks (Clark, 1980; Dockner et al., 1989; Plourde and Yeung, 1989; see Table 6.1). This corresponds to the so-called Schaefer technology in fisheries economics; that is, $h_i(t)=kz_i(t)x(t)$, with $h_i(t)$ denoting firm i's harvest rate in period t, z_i her fishing effort, x the common pool fish stock, and k a positive constant. Fishing efforts and fish stock levels have positive and constant marginal harvesting productivities.One reason for the popularity of this functional form is that it simplifies the mathematical modelling, especially of dynamic arguments.

In this chapter we will consider a harvesting function with positive but decreasing marginal productivities for individual fishing effort z_i and fish stock levels. In the case of fishing effort the decreasing marginal productivity feature seems a plausible assumption. Its empirical validity can presumably be expected to increase, the higher the scale of harvesting operations[3].

Decreasing marginal harvesting returns for the fish stock can be a more controversial assumption in terms of its empirical validity. To justify its use on these grounds, we would need to argue for the existence of some indivisible factor that negatively affects the marginal harvesting contribution of the fish stock as its level increases. A possible example is as follows. Suppose there occurs an exogenous increase in the availability of a given fish population. Imagine that this population distributes itseft in geographically dispersed and highly mobile fish patches. Suppose that the population growth implies, given food distribution patterns, that more dense fish patches tend to move to more distant and unknown sea grounds. In this example, it is reasonable to expect that the more abundant fish population will imply higher catches for a given level of the variable input fishing effort (i.e., number of fishing days). Nonetheless, as the closest fish patches become depleted, it is plausible to expect that the positive harvesting productivity of additional (more distant) fish patches will start to decline, given the fixed searching capacity (for locating fish patches) which is attached to each fishing boat (i.e., engine power, radar, crew captain's idiosyncratic fishing knowledge). We could interpret the declining productivity of the incremental (more distant) fish patches, *ceteris paribus*, as equivalent to an aggregate (though dispersed) fish stock with positive but declining marginal harvesting productivity.

The empirical relevance of an assumption is a possible, though not the only, criterion to evaluate its usefulness. In the model in this chapter, two other criteria have guided our choice of the assumption of declining marginal harvesting

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[3] As the scale of harvesting increases, it is plausible to expect that indivisibilities in the harvesting operation will start to negatively affect the marginal productivity of the variable input fishing effort. For instance, think of the crew captain's fishing ability, which is usually a non-easily reproducible idiosyncratic knowledge, as a possible source of an (implicit) indivisible factor within the harvesting technology.

productivity for the fish stock. First, a tractability argument: this assumption, together with a declining marginal productivity for fishing effort, allows us to obtain analytical solutions for our differential oligopoly harvesting games.

Second, a theoretical inquiry. The modelling of a decreasing marginal productivity for the fish stock will allow us to study oligopolistic overfishing incentives when individual firms face *increasing* marginal productivity losses as they (together) increase the harvesting competition aimed at appropriating the common pool resource's Ricardian rents. As the fish population decreases due to an increasing aggregate harvesting, each firm's marginal productivity of effort falls at an increasing rate. The latter effect is absent when the Schaefer harvesting technology is used.

Table 6.1 summarizes some key features of the most important fishery models which have been mentioned in this section. The next section analyses four of these models in greater depth, explaining how our model differs.

(6.C) A brief survey.

This section reviews four fishery models (Clark, 1980; Levhari and Mirman, 1980; Dockner et al., 1989; Plourde and Yeung, 1989) with some similarities to our modelling in this chapter. We do so in order to highlight the contribution of our analysis. The four models share some important common features:

(A.1) The focus is on dynamic and deterministic oligopoly harvesting models.

(A.2) They consider a common property and single fish stock fishery, subject to decentralized multi-firm harvesting. The number of harvesting firms is at least equal to two ($N \geq 2$).

(A.3) The fishery operates under closed entry. Accordingly, the number of harvesting firms N is an exogenous variable.

(A.4) Cooperative private harvesting arrangements are excluded by assumption. *Cooperation* is meant to imply *harvesting coordination*, in the sense of firms'

Table 6.1
Taxonomy of Main Reviewed Fishery Models

Models	Technological externality: congestion/stock	Price making (PM) vs. Price taking (PT) behaviour	Equilibrium concept	Objective function: single (S) vs. multi(M) period	Choice variable: closed loop (CL) vs. open loop (OL)	Harvesting technology
(1) Levhari and Mirman (1980)	Stock	PT (implicit): input and output markets.	Duopoly: Cournot-Nash and Stackelberg	M	Harvest rate h_i (CL)	Firm i's total cost function: linear in h_i (implicit)
(2) Clark (1980)	Stock	PT: input and output markets.	Duopoly: Cournot-Nash	M	Fishing effort z_i (CL)	$h_i = kz_ix$
(3) Kamien, Levhari and Mirman (1985)	Stock	PM: in output market	Duopoly: Conjectural Variations (Cournot-Nash as subcase)	M	Harvest rate h_i (CL and OL)	- Costless harvesting - No explicit harvesting function.
(4) Cornes, Mason and Sandler (1986)	Congestion (aggregate effect)	PM: in output market.	Oligopoly: Cournot-Nash	S	Fishing effort z_i	$H = F(Z), F' > 0, F'' < 0$; $h_i = [z_i/Z]F(Z)$ $H = \sum_{i=1}^{n} h_i$; $Z = \sum_{i=1}^{n} z_i$
(5) Mason, Sandler and Cornes (1988)	Congestion (aggregate effect)	PM: in output market.	Oligopoly: Conjectural variations (Cournot-Nash as subcase)	S	Fishing effort z_i	$H = F(Z), F' > 0, F'' < 0$ $h_i = [z_i/Z]F(Z)$
(6) Plourde and Yeung (1989)	Stock	PT (implicit): input and output markets.	Oligopoly: Cournot-Nash	M	Fishing effort z_i: state separable game $\rightarrow$ CL = OL	$h_i = z_ix$

Table 6.1. (continuation)

Models	Technological externality: congestion/stock	Price making (PM) vs. price taking (PT) behaviour	Equilibrium concept	Objective function: single(S) vs. multi (M) period	Choice variable: closed-loop (CL) open-loop (OL)	Harvesting technology
(7) Dockner et al. (1989)	Stock	PM: in output market.	Duopoly: Cournot-Nash and Stackelberg	M	Fishing effort z_i: state-separable game ⇒ CL = OL	$h_i = z_i x$
(8) Smith (1968)	Congestion ($\varnothing_N > 0$) and Stock ($\varnothing_x < 0$)	PT: input and output markets.	Free access: $\dot{N} = \delta \Pi_i$; $\delta > 0$; $\dot{N} = \frac{dN}{dt}$ Π_i = (symmetric) firm i's profits	S	Harvest rate h_i	firm i's total operating cost: $C_i = \varnothing(h_i, x, N)$; $\varnothing_1 > 0$, $\varnothing_2 < 0, \varnothing_3 > 0$ N: number of firms.
(9) Brown (1974)	Congestion and stock (non separable effects)	PT: input and output markets.	Welfare planner problem	M	Industry's fishing effort Z	$H = G(x, Z)$; $G{:}\,h.d.1$ and strictly concave ⇒ $(H/x) = g(Z/x), g' > 0, g'' < 0$ H: aggregate catch x: fish stock

harvesting strategies aimed at *internalizing* the dynamic externality. It is assumed that any attempt to coordinate individual harvesting decisions will imply higher coordination and enforcement costs than the expected benefits.

(A.5) A harvesting function $h=h(z,x)$ with h *linear* in z and x; where h denotes the harvest level, z a homogeneous variable input, and x the fish stock level. Input z represents the choice variable. Call it *fishing effort*. Think of input z as a variable that combines other inputs (for example, capital, labour, and services) in fixed proportions.

(A.6) Total harvesting costs are *linear* in the harvest rate. This occurs due to the combined effect of (i) firms' price taking behaviour in the market for input z, and (ii) the constant marginal productivity of z due to assumption (A.5).

(A.7) Suppose that any physical capital input is *perfectly malleable*. This means that it can adapt, without positive adjustment costs, to any desired level. This is consistent with the modelling of the composite input z as the only choice variable.

(A.8) A strictly concave biological growth function for fish stock x. This assumption is necessary to avoid multiple equilibria and related instability problems (see chapter 2).

Our modelling in this chapter shares these features, with the exception of the linearity assumption in (A.5). Instead we differ by assuming (i) a harvesting function that is *strictly concave* in z and x. Other sources of divergence with previous models are related to the assumptions on (ii) whether or not harvesting firms are endowed with price setting powers, and (iii) whether harvesting strategies are characterized as open-loop or closed-loop policies. Table 6.1 summarizes these and other key assumptions in the main previous fishery models which are related to our discussion in this chapter. Our dynamic model considers oligopolistic firms subject to price taking behaviour and closed loop fishing effort strategies.

Let us review the overfishing outcomes that result from the above mentioned four models in their treatment of Cournot-Nash and Stackelberg dynamic oligopoly harvesting fisheries.

(6.C.1) Cournot-Nash overfishing outcomes.

Clark (1980) studies a Cournot-Nash *duopolistic* fishery with features (A.1)-(A.8). He assumes *price taking* harvesting firms and focuses on *steady state* solutions. Each duopolist's fishing effort decision corresponds to a *closed-loop* policy: each current effort decision is a function of current fish stock levels. Given the use of a firm's objective functional (the profit function) that is *linear* in the control variable, the effort solutions correspond to *bang-bang* controls[4]. The optimality benchmark is a sole owner's harvesting policy. Asymmetric firms, in terms of harvesting efficiency, are considered. The *higher efficiency* firm is defined as having a lower *open access* equilibrium stock level at which the firm's profit becomes zero. A firm can be more efficient than her rival due to a lower cost parameter or because of a higher harvesting productivity coefficient.

The asymmetric efficiency case is used to examine the possibility of convergence to a sole owner's harvesting solution. This occurs when the higher efficiency firm drives the fishery to a sufficiently low stock solution such that it implies a non-positive profit margin for her rival. This will occur when one of the duopolists enjoys a sufficiently higher harvesting efficiency, in the sense defined above, as opposed to her rival. The model does not consider the possibility of re-entry competition, despite the fact that a sole owner firm will tend to choose a higher stock level equilibrium than the stock level that is required to drive her rival away.

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[4] A bang-bang solution implies that the control variable (fishing effort) can only takes its maximum ($z=z_{max}$) or its minimum value ($z=0$) when the fish stock differs from its steady state level. When the latter prevails, the fishing effort rate is such that the aggregate harvesting is equal to the natural biological growth $dx/dt= G(x)$.

The key element for the duopoly overfishing result is the assumption of Nash conjectures. A Cournot-Nash firm only considers the marginal effects, on the fish stock, arising from changes in her own harvesting level. Rivals' harvesting is taken as given. As long as the natural resource has a zero market price (given commonality), each Nash firm will not consider the effect that marginal changes in her rival's catch has over the social scarcity value of the common pool fish stock. Consequently, each firm will tend to undervalue the shadow price of fish stocks. Hence, the common pool stock will be driven to an inefficiently low level.

Plourde and Yeung (1989) is another overfishing model that focuses on a closed entry, deterministic and dynamic Cournot-Nash multi-firm fishery. This model generalizes the overfishing proof for the case of N>2, assuming features (A.1)-(A.8). It differs from Clark (1980) in its use of a logarithmic objective function, representing utility streams derived from the harvesting rate h. Harvesting technology h is *linear* in fishing effort and in fish stock, with fishing effort as the control variable. By using a *Gompertz* growth function[5] and a logarithmic transformation of the original state variable (fish stock), the authors obtain fishing effort solutions which are *open-loop* controls: effort solutions become independent of fish stock levels.

Despite the formal generalizations with respect to Clark's basic setting, the key message remains intact in Plourde and Yeung's (1989) results: Cournot-Nash conjectures lead to a multi-firm overfishing outcome. Although this model obtains an explicit solution for the Cournot-Nash firms' valuation of the common pool fish stock, it does not analyse whether or not static optimizing (myopic) behaviour is the limit case of this multi-firm fishery as the number of firms increases. Our modelling in sections (6.F) and (6.H), by contrast, offers an explicit analysis of the latter issue. This analysis considers Cournot-Nash and Stackelberg multi-firm fisheries.

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[5] The *Gompertz* growth function corresponds to: $\dot{x}(t)=x(t)[\alpha-\beta\ln\{x(t)\}]$.

(6.C.2) Introducing Stackelberg leadership.

Dockner et al. (1989) and Levhari and Mirman (1980) also consider deterministic and dynamic Cournot-Nash equilibria, but in addition analyse the case of a dynamic Stackelberg equilibrium. Both models focus on a *duopoly* harvesting sector.

Dockner et al. (1989) work with a harvesting fishery that faces a unit elasticity inverse demand function $p(H) = 1/H$, where the total harvest rate is $H=(h_1+h_2)$[6]. As a result, the duopoly firms face harvesting interdependencies that originate from two different sources:

(1) from the technological effect of (i) fish stock commonality, (ii) stock dependence of the firm i's harvesting function $h_i=z_ix$, with z_i denoting i's fishing effort and x for fish stock levels, and (iii) the impact of each firm's current harvesting over the future levels of the fish stock x; and

(2) from the market harvesting interaction that arises from the effect of harvesting output on price, given the assumption of $p'(H)<0$.

The model allows the duopolists $(i=1,2)$ to have different constant unit costs of fishing effort w_i, with firm i's total harvesting cost equal to $C_i=w_iz_i$. This model also considers a *Gompertz* growth function for the stock x, as in Plourde and Yeung (1989), and solves for an infinite horizon problem. Given the particular demand and harvesting functions considered, the fishing effort solutions become *open-loop* strategies. This implies that the dynamic optimization problem is solved by maximizing the current profit function in each time period, *as if* the decision maker were a static optimizing agent[7]. This means that, in this infinite horizon problem, the only relevant source of strategic interaction becomes the market interaction that arises from the effect of harvesting output on price (Dockner et al., p.5).

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[6] Note that the total revenue of the two firms (pH) is constant given the unit elastic demand function.

[7] Firm i's per period profit is $(px-c_i)z_i$. The inverse demand function implies $p=x^{-1}(z_i+z_j)^{-1}$. Hence the per period profits become independent of x.

The *steady state* solutions from Dockner et al. (1989) can be summarized as follows. Denote industry's total fishing effort by Z^e, with the superscript e=S,N denoting equilibrium type (Stackelberg and Cournot-Nash equilibria, respectively); Π^e denotes total profits in the industry with equilibrium type e (e=S,N); whereas Π_j corresponds to player j's profits, with j=L,f for leader and follower, respectively. The industry's total profit is the sum of both firms' individual profits. Similarly, c_j denotes firm j's constant per unit cost of fishing effort. The steady state solutions are:

(A) if $w_L > w_f$, then $Z^S < Z^N$ and $\Pi^S > \Pi^N$; with $(\Pi_L)^S > (\Pi_L)^N$ and $(\Pi_f)^S > (\Pi_f)^N$.

(B) if $w_L < w_f$, then $Z^S > Z^N$ and $\Pi^S > \Pi^N$,[8]; with $(\Pi_L)^S > (\Pi_L)^N$

The welfare maximization solution is not derived to compare with the oligopoly equilibria[9]. Hence, it is not possible to make welfare prescriptions that refer to *overfishing* outcomes. However, some lessons result from comparing the Cournot-Nash and Stackelberg solutions:

(i) In both equilibria the firm with cost advantages achieves the higher stationary catch rate. This is independent of whether that firm has Stackelberg leadership. Hence, if the Stackelberg leader has cost disadvantages with respect to the follower ($w_L > w_f$), the leading firm will choose a lower fishing effort than the follower's one.

(ii) If the firm endowed with Stackelberg leadership has cost advantages over the follower, she will choose a higher fishing effort than in the case she used Cournot-Nash conjectures. If the Stackelberg leader has cost disadvantages, by contrast, she will choose a lower fishing effort than in the case she used Cournot-Nash conjectures.

According to the results in (A) and (B), in Dockner et al. (1989) the presence of Stackelberg leadership implies higher industry's stationary fishing efforts (versus the Cournot-Nash case) only if the leading firm has cost advantages over the follower. If not, the leading firm will reduce her fishing effort in order to allow for

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[8] This requires equality of the discount rates of the duopolists.

[9] Note that since $p=p(H)$, $p'(H)<0$, welfare measures must include a consumers' surplus term as well as the firms' profits.

a higher demand price. The resulting aggregate fishing effort will be lower than in the corresponding Cournot-Nash equilibrium.

Let us now consider the fourth and last model under review. Levhari and Mirman (1980), hereinafter LM, is a dynamic and deterministic duopoly harvesting game, where each player maximizes a per period payoff that is logarithmic in his catches. Players can only differ due to asymmetric discount rates, apart from their different roles as leader and follower. The harvest rate h_i is each player i's choice variable. The model has no explicit harvesting function. Similarly, there is no explicit harvesting cost function, although it is possible to deduce an implicit harvesting cost function which is *linear* in the harvest rate[10]. The model excludes firms with price setting powers, in contrast with Dockner et al. (1989).

The strategic interaction between harvesting firms arises from the common property of the fish stock x. For each time period, each player's harvest is equal to the available fish stock net of his rival's catches and the remaining stock that is left for future fish growth. The remaining end of period fish stock, weighted by a percentage share parameter, is also an argument within each player's logarithmic payoff function. As a result of the particular explicit functions that this model uses, the stationary harvesting solutions always correspond to *closed-loop* strategies; where the fish stock x corresponds to the state variable and the harvest rate to the control variable.

By using an identical notation to that of our previous discussions, we can summarize the *stationary* solutions from LM's model as follows[11]:

[10] In LM's model there is no explicit market for catches. In the reduced form of this model, each agent i' utility function is logarithmic in his own harvest rate h_i. A possible structural model can be as follows. Suppose firm i's profit is $\Pi_i = ph_i - c(h_i)$ and utility is $u_i = u(\Pi_i)$. If $c(h_i) = kh_i$ then $u_i = u((p-k)h_i)$. Given a logarithmic utility function, we have $u((p-c)h_i) = \ln(h_i) + \ln(p-c)$. But $\ln(p-c)$ is a constant; hence the latter expression will have no effect on optimal h_i behaviour. Hence LM's reduced form remains valid.

[11] We concentrate on the case of duopolists with identical discount rates.

(a) $H^J > H^N > H^S$; with an *ambiguous* result for the leader's catches, as this result depends on the parameters of the model; and

(b) $x^J > x^N > x^S$; with x denoting the steady state fish stock,

where "J" denotes the outcome for the joint optimization (of both players' utility) case. This corresponds to the welfare benchmark used by LM (1980).

The results in (b) show an overfishing outcome for both Stackelberg and Cournot-Nash solutions, but with a bigger departure from efficiency for the Stackelberg case. The stationary aggregate harvest ranking, that is shown in (a), is a consequence of the overfishing solutions for the steady state fish stocks. What explains the higher overfishing result for the Stackelberg equilibrium?

The key element is the leader's first mover advantage, *without* cost disadvantages versus rivals and *without* demand price penalties (given the implicit firms' price taking behaviour[12]), that allows him to anticipate (or preempt) harvesting from his rival. The leader does not face higher marginal harvesting costs as he increases his catches. He only observes a decreasing marginal increase in his total payoff, given the logarithmic feature of the payoff function. As a result of this incentive structure, a Stackelberg leader will decide to catch more than a Cournot-Nash player in each period. If he does not do so, the follower will increase his own current harvests.

Then, what stops the leader from endlessly increasing his current harvesting? First, the strict concavity in catches of his payoff function.[13] Second, his lower payoffs as the remaining end of period fish stock decreases. An important parameter in this latter effect is the percentage share that the leader enjoys over the total remaining fish stock. In LM's model, this parameter is equated to a half. A higher

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[12] In LM's model there is no explicit market for fish. Since each firm's utility function depends only on its own catch, firms are either consuming the catch or selling it in a market at a given price.

[13] So that the leader would prefer a constant harvest to a declining harvest, with the same total catch over time.

share in final stocks could compel him to be a more *conservationist* player. But the key point in this model is that if one player does not currently harvest the available fish stock, the rival player will costlessly do so. If we assign a higher (parametrized) share in final fish stocks to one of the players, he has incentives, *ceteris paribus*, to invest more in them. But the opposite effect will result for the other player: he will want to increase his current harvests. Therefore, each player will engage in a current harvesting competition with the rival firm.

The key incentive issue in this model is that an unilateral increase in current harvesting by one of the players, for a given share of final fish stocks, also involves incentives for the rival to increase his own current harvesting. Because the leader makes use of his first mover advantage in anticipating harvesting, reducing the remaining fish stock, and because symmetric harvesting costs do not increase as the fish stock falls, the leader's higher current harvest will also induce the follower to catch more during that period. Accordingly, we obtain the higher Stackelberg overfishing outcome versus the case of a fully Cournot-Nash fishery.

In the sections that follow we develop our own model with different equilibrium concepts. In each case we obtain explicit solutions for the oligopolistic firms' valuation of the common pool fish stock and we derive formal proofs of oligopoly overfishing. In the case of a dynamic Cournot-Nash multi firm fishery, we discuss whether individual harvesting myopia (i.e., static profit optimizing behaviour) is the limit case of this type of fishery as the number of firms increases.

When we discuss a hierarchical Stackelberg multi firm fishery, we focus on the case of a *single* dynamic optimizing agent who competes in harvesting with $n > 1$ static optimizing rivals. In this setting the main motivation is to examine how the dynamic optimizing firm's harvesting incentives are affected by the entry of an increasing number of rival firms into the common pool fishery. The resulting industry's harvesting is then compared with first best and second best welfare benchmarks, and with three different definitions of a Cournot-Nash multi-firm harvesting fishery.

(6.D) The basic setting for analysis.

In this section we describe the main assumptions that we use in the analysis that follows. In order to avoid instability issues that can arise from non-concavities in the growth function for the single species fish stock (see chapter 2), we will assume a strictly concave logistic law of natural growth:

$$G(x) = \dot{x} = ax\left(1 - \frac{x}{K}\right) \qquad \text{(D.1)}$$

where $\dot{x} = dx/dt$

x: fish stock

a: instantaneous growth rate, $a > 0$

K: Nature's carrying capacity, $K > 0$; i.e., the dynamic system's long run equilibrium if harvesting is zero.

All variables in our model are defined for a given time index t (i.e., $x = x(t)$). In order to simplify notation we omit t. Additionally, we will choose units so that $K = 1$.

We consider a Cobb-Douglas harvesting technology and follow the specialization proposed by Leonard and Van Long (1992, p.295) that allows us to obtain an analytical solution[14]; that is:

$$h_i = z_i^{1/2} x^{1/2} \qquad \text{(D.2)}$$

where h_i is firm i's harvesting and z_i is firm i's fishing effort.

[14] Constant returns to scale are necessary in order to obtain an analytical solution. Numerical analysis could be used to generalize for other parametric combinations such that $\alpha + \beta = 1$.

We might also want to consider a static or congestion externality. One possibility is to include rivals' fishing effort with negative impact on h_i. However, this introduces static as well as dynamic strategic considerations and makes the analysis overly complex. We do not consider this option, given our desire to emphasize the *dynamic* part of the strategic interaction.

We also make the following assumptions:

(a.1) The price p of a unit harvested from x is constant over time and independent of industry harvesting. We therefore choose monetary units so that $p=1$ and h_i measures value of harvests.

(a.2) There are no fixed costs. Consequently, total harvesting cost $C_i = wz_i$, where w is the constant average and marginal cost of fishing effort.

(a.3) There are no storage possibilities. Accordingly, current sales and profits only depend on current harvesting.

(a.4) All prices are constant and known with certainty.

Initially we consider the case of *identical* firms. At a later stage (section 6.H), we relax this symmetry condition. The total number of firms is given and equal to N, where $n=N-1$ is the number of followers in the Stackelberg case.

Notation Summary

x	single species fish stock level.
z_i	firm i's fishing effort.
z_{-i}	total fishing effort from i's rival firms.
p	selling price for harvest output.
w	per unit cost of fishing effort.
h_i	firm i's harvest level.
N	total (exogenous) number of firms.
n	number of followers in Stackelberg case.

a instantaneous growth rate of x, $a>0$.

r discount rate.

$\lambda=\lambda_w$ welfare planner's (shadow) scarcity value for x.

λ_n equilibrium scarcity value of x in a Cournot-Nash setting.

λ_S equilibrium scarcity value of x in a Stackelberg setting.

(6.E) A first best welfare benchmark.

In this section we define and solve for a first best optimality benchmark. In the next sections we compare this solution with non-cooperative Cournot-Nash and Stackelberg equilibria. By doing so, we analyse overfishing propositions.

Suppose a social planner whose objective is to maximize the discounted value of the intertemporal flow of the natural resource's rents. The resource's rents are equivalent to the sum of the individual firms' profits. Imposing the symmetry condition across the N firms and, hence, writing $z_i = z$,$\forall i$ with $i=1,..,N$, to denote the fishing effort of the representative firm, the planner's problem consists in choosing z such that:

$$Max_z\ V = \int_0^\infty e^{-rt} N(z^{1/2}x^{1/2} - wz)dt \tag{E.1}$$

where $0<r<1$ is the time (constant) discount rate, and the dynamic constraint is given by:

$$\dot{x} = ax(1-x) - N(z^{1/2}x^{1/2}) \tag{E.2}$$

with $z\geq 0$, $x>0$ and $x(0)=x_0>0$.

Given the strict concavity of each firm's profit function implied by the decreasing marginal productivity of z, the optimal z_i^* will be a strictly positive interior solution[15].

To solve problem (E.1)-(E.2) we maximize the following Hamiltonian function H at each time period t:

$$Max_z\ H = e^{-rt}N(z^{1/2}x^{1/2} - wz) + \Omega(ax(1-x) - Nz^{1/2}x^{1/2}) \tag{E.3}$$

where Ω is the present valued shadow price of a marginal unit of investment in capital stock x.

The first order conditions for the solution are given by:

$$\partial H/\partial z \leq 0,\ z^* \geq 0 \text{ and } [\partial H/\partial z]z^* = 0 \tag{E.4}$$

$$\dot{x} = \partial H^*/\partial \Omega, \text{ where } H^* = H(z^*) \text{ and } z^* \text{ is the optimal value of z given by (E.4)} \tag{E.5}$$

$$\dot{\Omega} = -\partial H^*/\partial x \tag{E.6}$$

$$\lim_{t\to\infty} \Omega(t)x(t) = 0^{16} \tag{E.7}$$

Let us redefine this problem in order to get a time autonomous dynamic system that can be analyzed using phase diagram techniques. This allows a qualitative characterization of the optimal solution. We do so by defining the current valued Hamiltonian H^c:

$$H^c = N(z^{1/2}x^{1/2} - wz) + \lambda(ax(1-x) - Nz^{1/2}x^{1/2}) \tag{E.3'}$$

where $H^c = e^{rt}H$ and λ is the current valued shadow price for x; that is:

$$\lambda = \Omega\, e^{rt} \tag{E.8}$$

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[15] Due to the decreasing returns in fishing effort, the marginal productivity of z will tend to infinite as $z \to 0$; therefore, the optimal level of z will be strictly positive.

[16] (E.7) requires that at the terminal date T, the capital stock x is either exhausted or, being $x(T) > 0$, its marginal present value be equal to zero. This means that when the optimizing period approaches $T \to \infty$, no additional value (gains) remains from using capital stock x.

The first order conditions from (E.4) to (E.7) remain valid for the new Hamiltonian H^c, although (E.6) is now replaced by:

$$\dot{\lambda}=r\lambda-\frac{\partial H^c}{\partial x}=\lambda[r-a(1-2x)]-\frac{1}{2}z^{1/2}x^{-1/2}(1-\lambda)N \tag{E.6'}$$

The existence of at least one maximum is guaranteed if the Hamiltonian function is *jointly concave* in x and z. Joint concavity requires that $[H_{zz}H_{xx}-H_{xz}H_{zx}]\geq 0$, where subscripts denote partial derivatives (see Chiang, 1992, ch. 4.2). The parametric configuration of our model satisfies this concavity condition, although we cannot ensure *strict* joint concavity ($[.]>0$) to fulfil the sufficient condition for a unique maximum. However, we deal with this issue by specializing our analysis on the uniquely convergent positive steady state equilibrium that in this model corresponds with the stable branch of a saddle point. We prove this in Appendix 6.1.

First order condition (E.4) gives the optimal value of z as a function of x and λ; that is:

$$[\frac{1}{2}(1-\lambda)(z^{*})^{-1/2}x^{1/2} - w]z^{*} = 0 \tag{E.9}$$

This implies that if $\lambda\geq 1$, then $z^*=0$. Given that the market value for a harvest unit is 1 ($p=1$), this condition simply says that if the planner assigns a higher value to an additional unit of x, then the optimal policy is to stop the harvesting of x completely.

If $0\leq\lambda<1$, then (E.9) implies:

$$z^{*} = \left[\frac{1}{2w}\right]^2(1-\lambda)^2x \tag{E.9'}$$

Replacing $z^*(x,\lambda)$ into (E.5), we obtain:

$$G(x,\lambda) \equiv \dot{x} = ax(1-x) - A(1-\lambda)x \quad , \quad A = \frac{N}{2w} \tag{E.10}$$

A similar process using (E.6') implies:

$$S(x,\lambda) \equiv \dot{\lambda} = \lambda(r - a(1-2x)) - \frac{A}{2}(1-\lambda)^2 \tag{E.11}$$

(E.11) implies that if $\lambda \geq 1$, hence $z^* = 0$, then the locus $\dot{\lambda}=0$ in (x,λ) space (see Fig. 6.1) describes a vertical line at $x=(1/2)[1-(r/a)]$. Equations (E.10)-(E.11) describe the dynamics of our system in terms of the capital stock x and its shadow price λ. From (E.9') we can obtain the optimal time path for z^*.

Let us concentrate on the *long run* behaviour of our system. The steady state solution is obtained from setting G(.)=S(.)=0. In fact, $\dot{x}=0$ implies[17]:

$$\lambda = (1 - a/A) + (a/A)x \quad , \quad A = \frac{N}{2w} \tag{E.10'}$$

Using (E.10) and the result that $z^*=0$ if $\lambda \geq 1$, locus $\dot{x}=0$ is defined by two different regions: If $\lambda \geq 1$ then locus $\dot{x}=0$ defines a vertical line at $x=1$.[18] If $0<\lambda<1$ and $0<x<1$, this locus defines a positively sloped linear function between λ and x, with slope a/A and (1- a/A) intercept at λ-axis.

When $\lambda \geq 1$ locus $\dot{\lambda}=0$ is defined by a vertical line at $x=(1/2)[1-(r/a)]$; if $0<\lambda<1$, (E.11) implies:

[17] We exclude the feasible steady state solution implying $x^*=0$ because it cannot be the optimal solution to the planner's problem. We have seen that the planner's optimal z^* should be strictly positive. But this requires that $x^*>0$, hence $h^*>0$, in order to be consistent.

[18] Notice that $x=1=K$ is the largest possible steady state stock, corresponding to zero harvesting.

$$x = B\frac{(1-\lambda)^2}{\lambda} + \frac{1-(r/a)}{2} \quad , \quad B = \frac{N}{8aw} \qquad \text{(E.11')}$$

In the space (λ,x), this locus starts at $\{1,(1/2)[1-(r/a)]\}$ and then λ decreases as x increases; as $\lambda \to 0$, (E.11') implies $x \to \infty$.

The phase diagram in Figure 6.1 summarizes this information. The steady state equilibrium (x^*,λ^*), with $0<\{1-(r/a)\}/2<x^*<1$ and $0<\lambda^*<1$[19], is a saddle point[20] (see Appendix 6.1). This means that, for each stock level x, there exists a unique trajectory that converges to the steady state equilibrium. Given any initial stock level x_0, the planner chooses the optimal fishing effort $z^*>0$ such that the resulting shadow value λ of the remaining stock falls on the convergent trajectory to the steady state. The fulfillment of the Transversality condition (E.7) ensures that the shadow price λ will be on the convergent trajectory to the stationary equilibrium (Chiang, 1992, p.124). This trajectory corresponds to the optimal path.

The convergent trajectory corresponds to the stable arm (curve TT') of the saddle point. This phase trajectory necessarily passes through regions I and III with negative slope (Appendix 6.1). In fact, from (E.10)-(E.11) we can verify that $S_x>0$, $S_\lambda>0$, $G_\lambda>0$ and $G_x<0$, in the vicinity of the steady state equilibrium E. This information allows us to draw arrows of motion like those depicted at regions I-IV.

In order to achieve the unique convergent positive steady state equilibrium (point E) the planner must choose an optimal effort level z^* such that allows him to locate the dynamic system (E.10)-(E.11) on the stable arm TT'. For instance, if initial conditions are such that $x_0<x^*$, the planner must choose an initial z^* such that

---

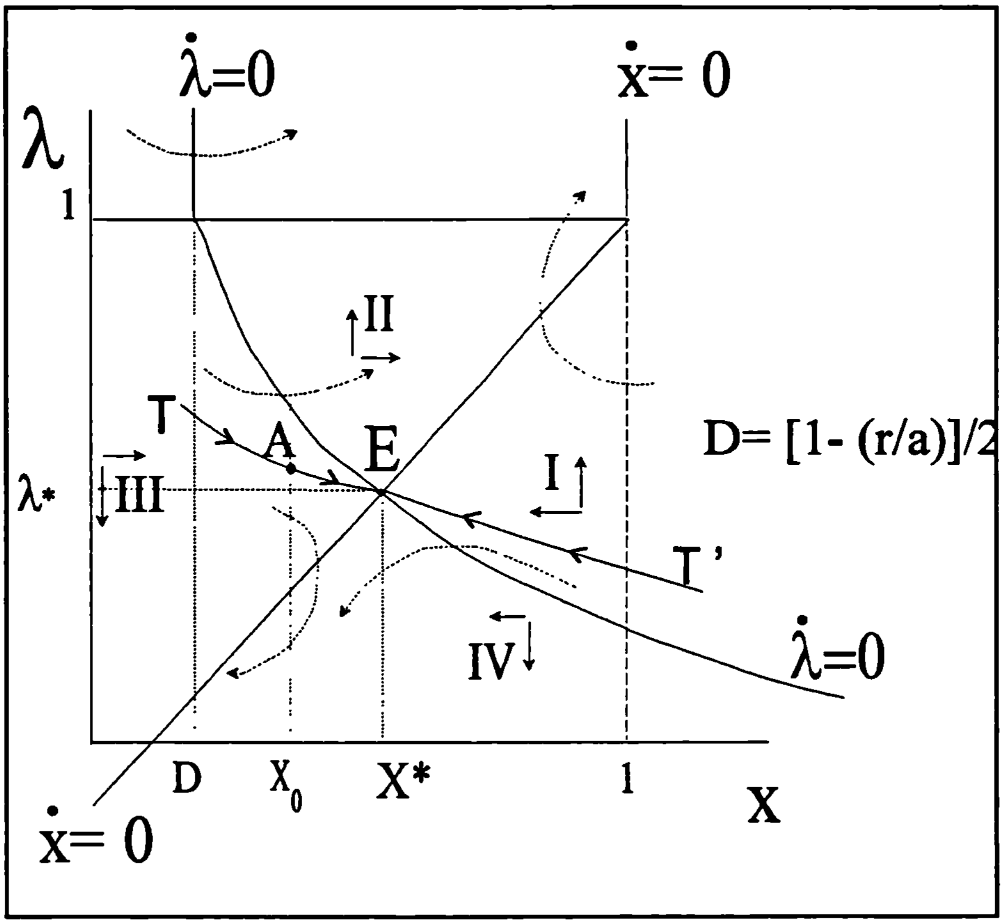
[19] Notice that we restrict our analysis to strictly positive values for x^*,λ^*. Hence, we will assume that invariably $r<a$. The concavity condition does not rule out negative solutions for x and λ, though no economic interpretation can be given to such a case.

[20] Using a harvesting technology linear in x and defining a law of motion for fishing effort (dz/dt) that is proportional to current profits (with an entry equation, for example), we can obtain a steady state solution with *limit-cycle* characteristics (see Leonard and Van Long, 1992, p.105).

the resulting $\lambda_w = \lambda_0$ locates itself on a point such as A in Figure 6.1. Once located on the stable arm, the dynamic forces of system (E.10)-(E.11) will drive it towards point E.

The adjustment process between points A and E will imply a recovery of fish stock x and, as a consequence of that, a reduction of its scarcity value λ_w. Given the optimal fishing rule in (E.9'), the planner will therefore be able to choose in the steady state equilibrium a higher level of optimal fishing effort (versus its level in point A). The resulting higher long run equilibrium for the harvest rate h^* represents the benefit stemming from the initial restrictions on z^* that allow for the recovery of the fish population x.

Figure 6.1
First best welfare case: steady state solution



(6.F) A Cournot-Nash equilibrium.

In this section we first solve for a dynamic (profit) optimizing multi firm Cournot-Nash fishery and we develop a formal proof of Cournot-Nash overfishing. Second, we briefly discuss the meaning of *myopic* decision rules, making a distinction between static (profit) optimizing rules and Pareto inefficient harvesting myopia. We then explore the effect of an increasing number of firms, with access to the common pool fish stock, upon the magnitude of the Cournot-Nash overfishing. We obtain a non-monotonic relationship between these variables.

Envision a fishery with N non-cooperative harvesting firms. Assume that these firms are *symmetric* Cournot-Nash players, implying that the representative firm i makes a decision on z_i subject to the conjecture that (a) $[\partial z_{-i}/\partial z_i]^c=0$ where z_{-i} is the fishing effort of firm i's rivals, and (b) all firms move simultaneously (deciding on z_j , j:1,....,N).

The optimizing problem for the representative firm i is:

$$Max_{z_i}\ V_i = \int_0^\infty e^{-rt}(z_i^{1/2}x^{1/2} - wz_i)dt \qquad \text{(F.1)}$$

subject to:

$$\dot{x} = ax(1-x) - \sum_{j=1}^{N} z_j^{1/2}x^{1/2} \qquad \text{(F.2)}$$

and $z_i \geq 0$, $x > 0$, $x(0)=x_0$, $w > 0$, $0 < r < 1$, where discount rate r, price p and cost w are the same as in the welfare case.

The relevant current valued Hamiltonian is:

$$H = z_i^{1/2}x^{1/2} - wz_i + \lambda_i\ [ax(1-x) - \sum_{j=1}^{N} z_j^{1/2}x^{1/2}] \tag{F.3}$$

where j:1,..,i,..,N and λ_i is firm i's shadow value for marginal investments at x. Note that Cournot-Nash firms are not assumed *ex ante* to behave as myopic profit optimizing agents, because they impose (F.2) on themselves as a constraint.

Since the Cournot-Nash firms are identical the first order conditions for the representative firm i are:

$$[\frac{\partial H}{\partial z_i}]z_i^* = [\frac{1}{2}z_i^{-1/2}x^{1/2}(1-\lambda_i) - w]z_i^* = 0 \tag{F.4}$$

$$\dot{x} = ax(1-x) - Nz_i^{*1/2}x^{1/2} \tag{F.5}$$

$$\dot{\lambda}_i = \lambda_i(r - a(1-2x)) - \frac{1}{2}z_i^{*1/2}x^{-1/2}(1-N\lambda_i) \tag{F.6}$$

$$\lim_{t\to\infty}[\lambda_i(t)e^{-rt}]x(t) = 0 \tag{F.7}$$

Note that (F.7) is fulfilled, if $r>0$, for any bounded $\lambda_i(t)>0$.

We can easily verify a clear similarity, for a given value of z*, between the structure of the equations that describe the first order conditions (F.4)-(F.5) for the representative Nash firm, and the corresponding first order conditions for the welfare case (E.4)-(E.5). However, if we compare (F.6) with the corresponding first order condition for the welfare planner (E.6'), we could anticipate that for a given value of z^* a Nash firm will assign a lower marginal value to the stock x vis-a-vis the value assigned by the planner. This derives from the fact that $\partial H/\partial x$ is lower for the representative Nash firm than in the case of the planner[21]. And it is precisely this

[21] Because the total gain to all firms from an increase in x is greater than for one firm.

partial derivative that measures the value assigned to an additional unit of investment in capital stock x, where this capital value includes both current and future net benefits.

The previous outcome anticipates the origin of the incentives for overfishing in the case of Cournot-Nash firms. The lower capital value assigned to x should imply a lower λ_i when compared to its equivalent in the welfare case. This should bring about heavier harvesting in earlier periods, thereby implying a lower x^* in the long-run. The reason underlying this result is the common property of x. If, to the contrary, it were feasible to assign efficient prices to x (either via market forces or regulation), then each firm i's fishing decision would include the economic costs of using additional units of a non-free good such as x. These are the intuitions. Let us now proceed with the conditions that prove them to be valid.

From (F.4) we deduce that if $\lambda_i \geq 1$ then $z_i^* = 0$; otherwise:

$$z_i^* = \left[\frac{1}{2w}\right]^2 (1-\lambda_i)^2 x \tag{F.4'}$$

Substituting this into (F.5) and (F.6), we obtain:

$$G(x,\lambda_i) \equiv \dot{x} = ax(1-x) - A(1-\lambda_i)x \quad , \quad A = \frac{N}{2w} \tag{F.8}$$

and

$$S(x,\lambda_i) \equiv \dot{\lambda}_i = \lambda_i(r - a(1-2x)) - \frac{A}{N2}(1-\lambda_i)(1-N\lambda_i) \tag{F.9}$$

Equations (F.8)-(F.9) describe the dynamics of the Cournot-Nash system. By setting both equations equal to zero we can determine the steady state Nash equilibrium. In this Cournot-Nash setting, denote the *equilibrium* solution for the representative firm's valuation λ_i by λ_n. We can see that the isocline $\dot{x}=0$ is identical in both the Nash and the welfare cases (see (E.10)). For the isocline $\dot{\lambda}=0$, (F.9) implies:

$$x = B\frac{(1-\lambda_n)(1-N\lambda_n)}{\lambda_n} + \frac{1-(r/a)}{2} \quad , \quad B=\frac{1}{8aw} \tag{F.9'}$$

As in the welfare case, if $\lambda_n \geq 1$ the locus $\dot{\lambda}=0$ defines a vertical line at $x=(1/2)[1-(r/a)]$. For $0<\lambda_n<1$, the difference between the Nash and the welfare cases becomes evident. As we anticipated, this is related to the (capital) value assigned to x. The slope of this locus, for both the Nash and the welfare cases, is given in Table 6.2:

TABLE 6.2

Cases	$\frac{\partial\lambda}{\partial x}\Big\vert_{(\dot{\lambda}=0)}$
Welfare (m^w):	$-\dfrac{8aw}{N[\frac{1}{\lambda^2}-1]} < 0 \quad , \forall\ 0<\lambda<1$
Cournot-Nash (m^n):	$-\dfrac{8aw}{(\frac{1}{\lambda_n^2}-N)} \gtrless 0 \ \ \mathit{if}\ \ \lambda_n \gtrless \dfrac{1}{\sqrt{N}}$

We define $m^i \equiv [\partial\lambda_i/\partial x]_{\dot{\lambda}=0}$, with $i=w,n$ for the welfare planner and the representative Cournot-Nash firm, respectively. We see that always $m^w<0$ for $0<\lambda<1$. To the contrary, $\mathrm{sign}[m^n]=-\mathrm{sign}[\{1/(\lambda_n)^2\}-N]$. Given $N\geq 2$, as λ_n approaches 1, locus $\dot{\lambda}=0$ will show a positive slope. This slope becomes steeper as λ_n falls, eventually becoming a negatively sloped curve that asymptotically approaches the x-axis.

The corresponding Cournot-Nash steady state equilibrium (λ_n,x_n) is shown in Figure 6.2. Again the steady state equilibrium corresponds to a saddle point

(Appendix 6.2). The fulfillment of the Transversality Condition (F.7) ensures that the system will move along the convergent trajectory TT'.

Figure 6.3 shows both the Nash and the first best welfare steady state equilibria, denoted by N and W, respectively. If $\lambda_n < (1/\sqrt{N})$, note that $m^n < 0$ such that $| m^n | > | m^w |$, (see Table 6.2). Consistently with the drawing at Figure 6.3, we can propose (for a formal proof see Appendix 6.3):

Proposition 1:

In our model, the steady state values for fish stock (x^*) and its shadow price (λ^*) imply that $(x^*)_n < (x^*)_w$ due to $(\lambda^*)_n < (\lambda^*)_w$, where subscripts n and w denote the Cournot-Nash and the first best welfare cases, with

$$\lambda_w^* = \frac{1}{2}\left[1 - \frac{N + 4Rw}{3N} + \sqrt{\left(1 - \frac{N + 4Rw}{3N}\right)^2 + \frac{4}{3}} \right] \tag{F.10}$$

and

$$\lambda_n^* = \frac{1}{2}\left[1 - \frac{1 + 4Rw}{3N} + \sqrt{\left(1 - \frac{1 + 4Rw}{3N}\right)^2 + \frac{4}{3N}} \right] \tag{F.11}$$

with $R = r + a$ and $0 \leq \lambda^* < 1$. Note that a sufficient condition for Proposition 1 to be valid is $(4Rw)/(3N) > 0$.

We can easily verify that solutions (F.10) and (F.11) become identical for N=1. This simply reflects the equivalence between sole ownership and Pareto efficiency when firms, that exploit a common pool resource, have price taking behaviour. Therefore, Proposition 1 states Cournot-Nash overfishing for a total number of firms $N \geq 2$.

We now state a distinction between *static* harvesting rules and *inefficient* Cournot-Nash harvesting, and afterwards we study how the latter outcome is affected by an increasing number of Cournot Nash firms with access to the common pool fish stock.

Figure 6.2

Cournot-Nash equilibrium

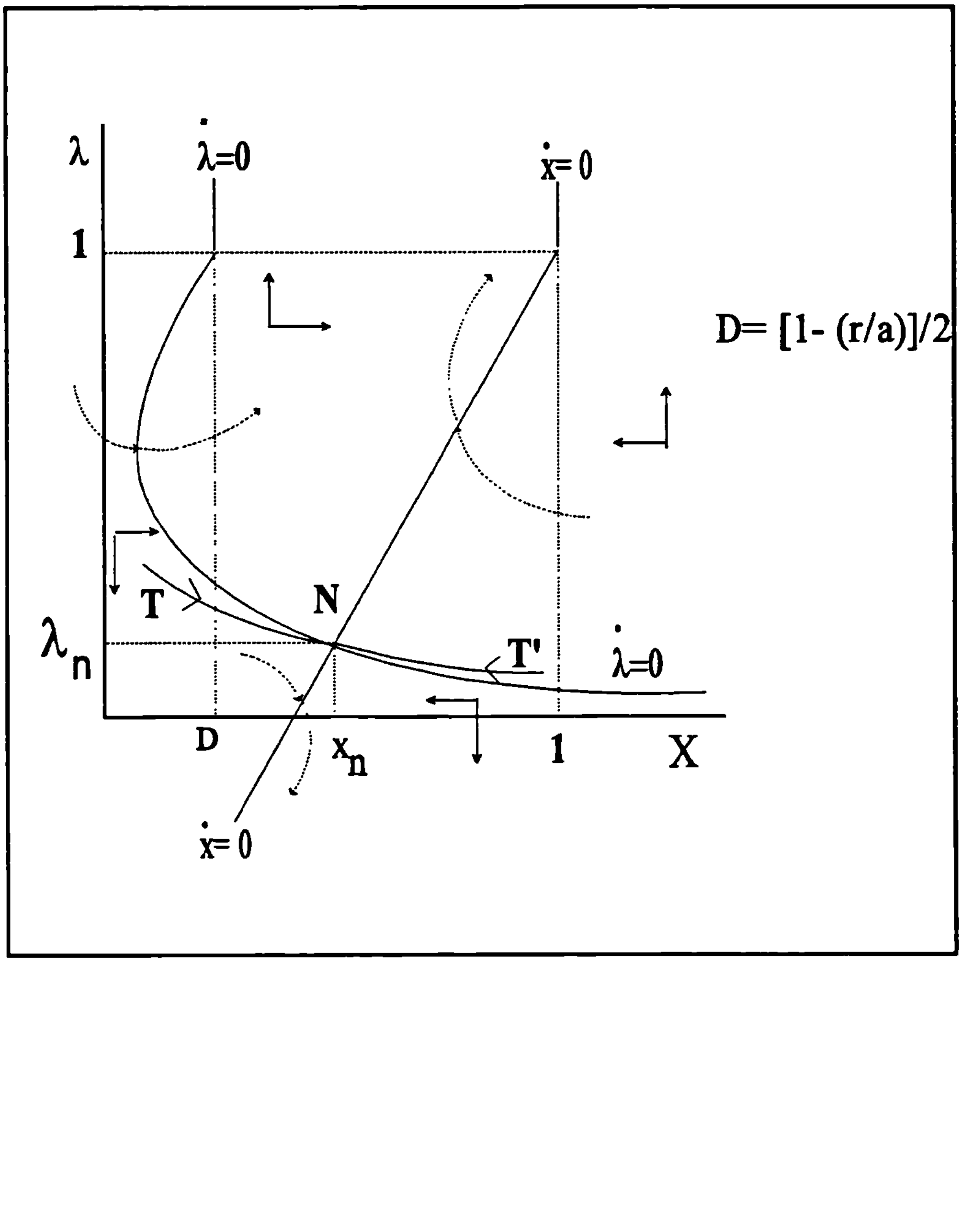
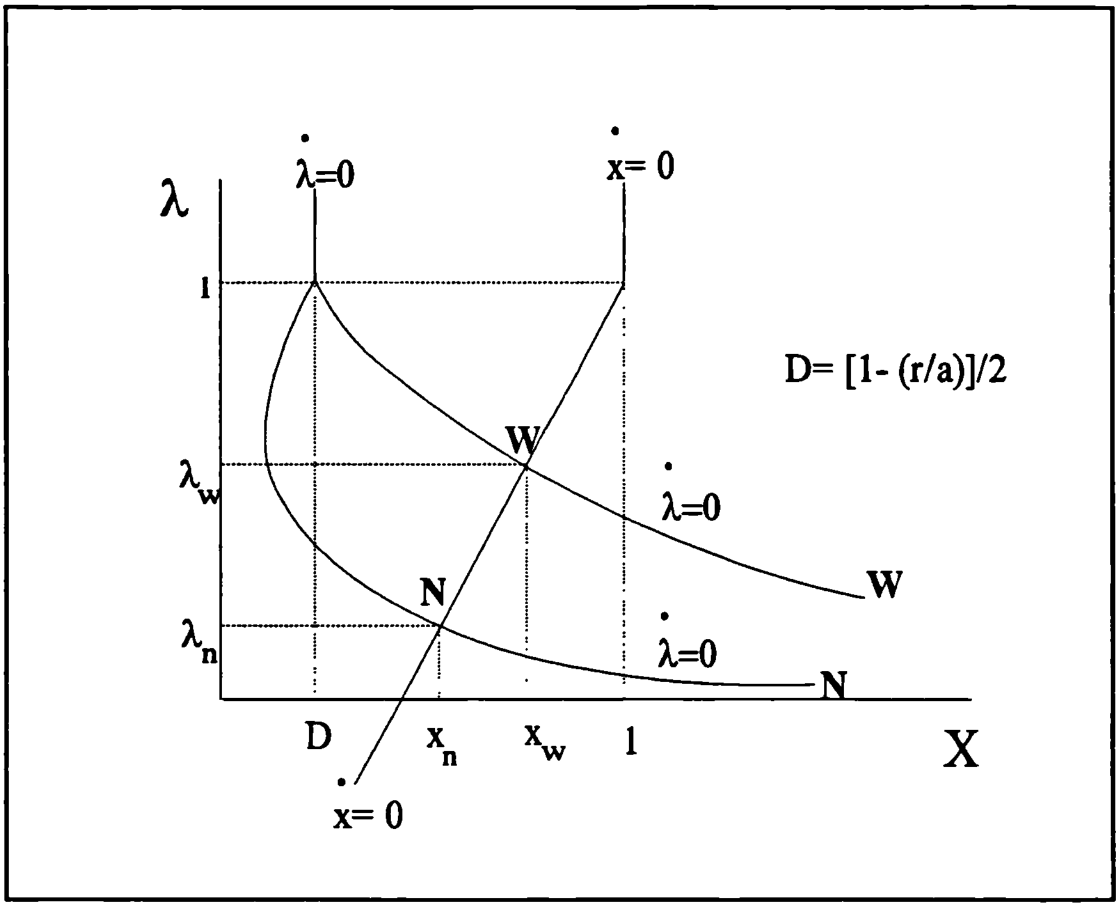


Figure 6.3

Cournot-Nash overfishing



(6.F.1) Myopic harvesting rules and inefficient overfishing.

At the heart of the traditional overfishing argument lies the intuitive idea that *numerous* and *small* non-cooperative harvesting firms will tend to ignore the effect of their actions on future fish stock because each bears only a small proportion of the cost of a smaller stock. As the number of firms increases, the intuitive proposition argues that the undervaluation of the social scarcity value will tend to increase (Gordon, 1954; Scott, 1955; Clark, 1980; Plourde and Yeung, 1989). We now formally analyse this proposition within our current multi-firm harvesting model. This makes it necessary to study solutions (F.10) and (F.11) in greater depth.

The implicit prices (F.10) and (F.11) show the steady state scarcity value that the corresponding optimizing agent assigns to the marginal unit of investment at x. If these shadow prices were equal to zero, this would imply that the optimizing decision maker acts as if resource x were freely available. In other words, the intertemporal resource constraint would no longer be perceived as binding. Accordingly, fishing effort would be chosen as if the decision context was static. In the literature, this type of result is called a *myopic decision rule* (Kurz, 1987).

Given our concern with *overfishing*, we want to define a harvesting myopia concept that considers an explicit measure of Pareto inefficiency:

Definition: We define *Pareto inefficient* (harvesting) *myopia* (PIM) as a fishing effort decision rule that *undervalues* the social scarcity value of x. Within the frame of our setting, the social scarcity value of x is given by the welfare solution λ_w^*.

Therefore, we will have Nash-PIM if $(\lambda_w^*-\lambda_n^*)>0$ as in Proposition 1[22]. In order to avoid confusions, when we have an inefficient *static* harvesting rule where $\lambda_i^*=0$ but $\lambda_w^*>0$, we will call this *fully myopic* harvesting.

[22] Notice that, for some particular modelling settings, $\lambda_w^*=0=\lambda_n^*$ could be possible. In this case we would have static optimizing behaviour but not inefficient harvesting myopia.

(6.F.2) Nash-PIM and an increasing number of firms.

We now study the effect of increasing the number N of firms on the Nash-PIM outcome derived in proposition 1, that is $(\lambda_w^*-\lambda_n^*)>0$.

We know that $\lambda_w^*=\lambda_n^*$ for N=1. We can also prove that both λ_w^* and λ_n^* monotonically increase as N becomes higher (see Appendices 6.4 and 6.5). At first sight this result might appear counter intuitive: traditional arguments (Gordon, 1954) would presumably have predicted that $\lambda_i \rightarrow 0$ as $N \rightarrow \infty$. What is then the intuition behind our result?

In our model, increases in the number of firms necessarily imply, *ceteris paribus*, that less x will be available because the industry's *aggregate* current harvest increases. And falls in x reduce, at an increasing rate, each firm's marginal productivity of effort. Hence, given the deterministic setting of this chapter, any dynamic profit optimizing agent should assign a higher scarcity value to the marginal unit of investment at x. The above argument represents the economic meaning that both $(\partial\lambda_w/\partial N)$ and $(\partial\lambda_n/\partial N)$ be invariably positive. We do not know other *dynamic* fishery models in which a result of this type have been formally derived.

If we consider the limit of the stationary solutions λ_w and λ_n, for $N \rightarrow \infty$, we obtain that in both cases the limit value is equal to 1 (Appendix 6.6). Given (E.9) and (F.4'), we know that a unitary value for the scarcity value λ implies an optimal policy of full closure for fishing ($z_i^*=0$) in the welfare and Cournot-Nash cases. Hence, for $N \rightarrow \infty$, it is unprofitable to continue with the commercial harvesting of x[23].

Dockner et al. (1989) develop a similar *limit* result to our case. They briefly explore a dynamic Cournot-Nash *multi-firm* fishery with identical *price making* firms.

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[23] If $\lambda_n^* \geq 1$ then $z_i^*=0$ (see condition F.4). By setting equation (F.8)=0 we also know that in any *stationary* equilibrium is must be true that $x^*=1-(1-\lambda^*)(N/2w)$. Hence, if $\lambda_n^* \geq 1$ then in the steady state $x^* \geq 1$ for $N \rightarrow \infty$. This implies the locally stable steady state $x^*=1$ (see equation D.1). Hence, the fish stock will not be harvested unless some parametric change (for example, a fall in N) transforms harvesting into a profitable activity.

A pecuniary externality, stemming from the effect of each firm's harvesting on demand price, is the center of firms' strategic interactions. Dynamic (fish stock) interactions become neutralized by the particular functional forms which are modelled (section 6.C.2). A negative relationship between the representative firm's stationary fishing effort and the total number N of firms is obtained. This results from a negative relationship between number of firms and equilibrium price. In the limit case $N \rightarrow \infty$, the market price is below the minimum average variable cost and hence the representative Nash firm shuts down ($z_i^* = 0$).

The roots behind the presumption that the Nash value $\lambda_n^* \rightarrow 0$, when the number of firms is sufficiently large, can probably be traced back to popular *static* discussions of overfishing. A clear example is Cornes, Mason and Sandler (1986)[24]. Key features of this Cournot-Nash multi-firm fishery model, with *static* profit optimizing firms, are shown in Table 6.1. Firms' interactions stem from a pecuniary externality effect (given firms' *price making* behaviour) and also from a technological congestion externality: each firm's catch is a proportional function (according with the share in industry's fishing effort) of the *aggregate* harvest which is a strictly concave function of aggregate fishing effort. Given the particular functional forms in use, the authors obtain that as the total number of firms gets larger each firm increasingly ignores the externality effects. When $N \rightarrow \infty$, the model shows the appealing result that each firm will equate the value of her average product to the marginal cost of fishing effort. Hence profits are driven to zero and the traditional *free access* (full rent dissipation) solution prevails.

In our *dynamic* Cournot-Nash model we do not obtain that $\lambda_n^* \rightarrow 0$ as $N \rightarrow \infty$. However, this result does not exclude the option that overfishing increases as N gets larger. The latter would require that $(\lambda_w^* - \lambda_n^*) > 0$ increases with a larger N. Hence,

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[24] See also the discussion in Dasgupta and Heal (1979, ch.3, pp.55-61).

we now ask: what happens with the difference $\Delta \equiv (\lambda_w - \lambda_n) > 0$[25] as the (finite) number $N > 1$ of firms increases? We study the qualitative behaviour of this effect by doing a numerical simulation exercise. Define parameter $b \equiv 4(r+a)w > 0$. If b increases, we expect that the scarcity value of the fish stock x should decrease (see F.10-F.11). This can occur either due to a higher discount rate r, a higher rate a of biological growth, or a more expensive per unit cost w of fishing effort. Therefore, for higher b values we should expect that both λ_w and λ_n become lower. But the effect on $\Delta > 0$ is not obvious on an *a priori* basis.

Figures 6.4 and 6.5 plot the values of the stationary solutions λ_w and λ_n (using equations F.10 and F.11) for an increasing number N of firms and for four increasing b values[26]. Each plotting specifies the corresponding simulation value of parameter b. Our exercise confirms a number of interesting results:

(i) For a given value of parameter b, we can observe the convergent processes, as N increases, of both solutions λ_w and λ_n towards the limit value of 1 (for $N \to \infty$).

(ii) The difference $\Delta \equiv (\lambda_w - \lambda_n)$ remains positive for different values of N, with the exceptions of $N=1$ and $N \to \infty$.

(iii) As the value of parameter b increases, we observe a consistent reduction in the steady state solutions for the scarcity value of marginal fish stock units, in each of the two equilibrium concepts that we are comparing (welfare and Cournot-Nash cases).

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[25] Given Proposition 1, $\Delta > 0$ insofar as $(4Rw)/3N > 0$, with $R = (r+a) > 0$ and $w > 0$.

[26] The simulated b values have no empirical support. We are only interested in studying the qualitative impact of increasing values of b on the solutions λ_w and λ_n. For $b = 4(r+a)w$, we only know that $0 \leq r \leq 1$, $a > 0$ is the rate of biological growth, and where the unit measure of the per unit cost $w > 0$ depends on the unit measure of fishing effort z_i. Firm i will be active as long as her profit $(pz_i^{1/2}x^{1/2} - wz_i) > 0$. Given that $p=1$, the positive profit condition implies that $w < [x/z_i]^{1/2}$. In steady state conditions, $0 < x \leq 1$; hence, $w > 0$ will be greater or lower than 1 depending on whether $z_i < (>) 1$.

(iv) As the value of parameter b increases, we tend to observe wider positive gaps between the steady state solutions λ_w and λ_n, for a given value of N. Figure 6.6 plots this result.

An interesting result is that higher values of b imply consistently higher positive differences $\Delta \equiv (\lambda_w - \lambda_n)$ for given values of $N > 1$. Let us examine the intuition behind this result: higher values of b imply that each Cournot-Nash firm assigns a lower scarcity value to stock x. For instance, a higher discount rate r makes future catches less valuable and hence reduces the incentives to invest in x. On the other hand, a higher growth rate a increases the future availability of x. Lower scarcity values of x increase, *ceteris paribus*, the representative firm's fishing effort (see equation F.4'). And higher values of the representative z_i^* imply that the use of passive Nash conjectures produces a bigger *under*estimation of the marginal changes in the industry's aggregate harvest[27]. Hence, the higher the level of the representative effort z_i^*, the bigger will be the overfishing stemming from the value gap $\Delta > 0$.

A second interesting result is the effect of increasing the number N of firms on the value gap $\Delta > 0$: for an initial range of relatively low N values, we obtain *increasing* positive values for the difference Δ as N gets larger (figure 6.6). Nonetheless, each b value implies a maximum positive difference $\Delta = \Delta^{max}$, after which increases in the number N of firms *monotonically reduce* the source ($\Delta > 0$) of the Cournot-Nash overfishing result. As $N \rightarrow \infty$, the difference $\Delta \rightarrow 0$. Therefore, we obtain that $(\partial\Delta/\partial N) > 0$ *only* for a limited (initial) range of $N > 1$ values. Once the maximum positive value of Δ is achieved, for a given b, higher values of N imply a monotonic convergence of both scarcity values λ_w and λ_n to the value of 1. This convergence implies a decreasing difference $\Delta > 0$. This result appears counter intuitive. Which factors lie at its roots?

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[27] Write the industry's harvest as $H = x^{1/2}(z_i^{1/2} + nz_j^{1/2})$, with z_j denoting the fishing effort of the representative *rival* firm j (existing n identical rival firms). If firm i uses Nash conjectures she estimates that $\partial H/\partial z_i = (1/2)(x/z_i)^{1/2}$. A social planner would additionally consider the changes in the fishing effort of symmetric rival firms j.

Figure 6.4

Scarcity values of the fish stock: Welfare and Cournot-Nash cases

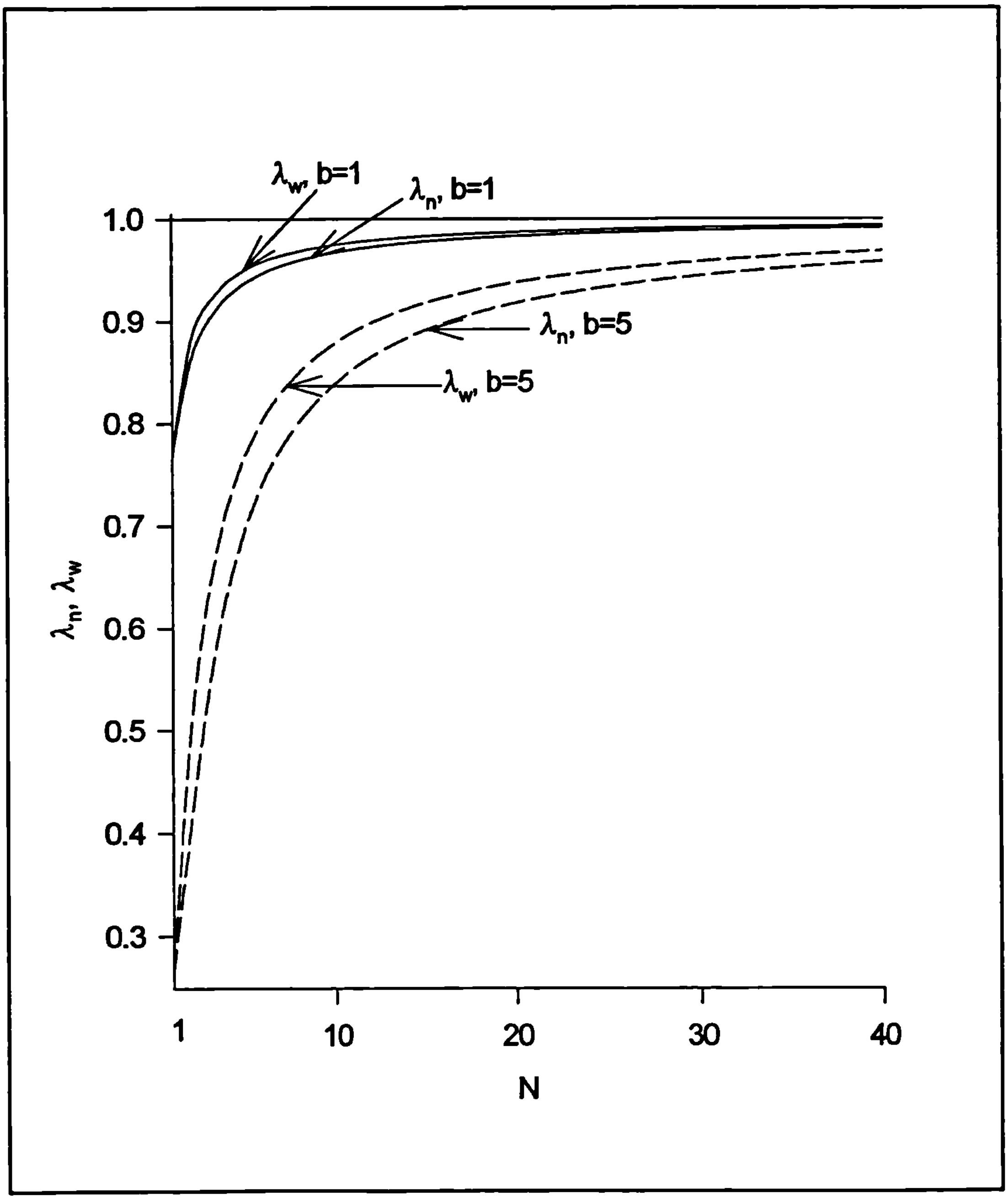


Figure 6.5

Scarcity values of the fish stock: Welfare and Cournot-Nash cases

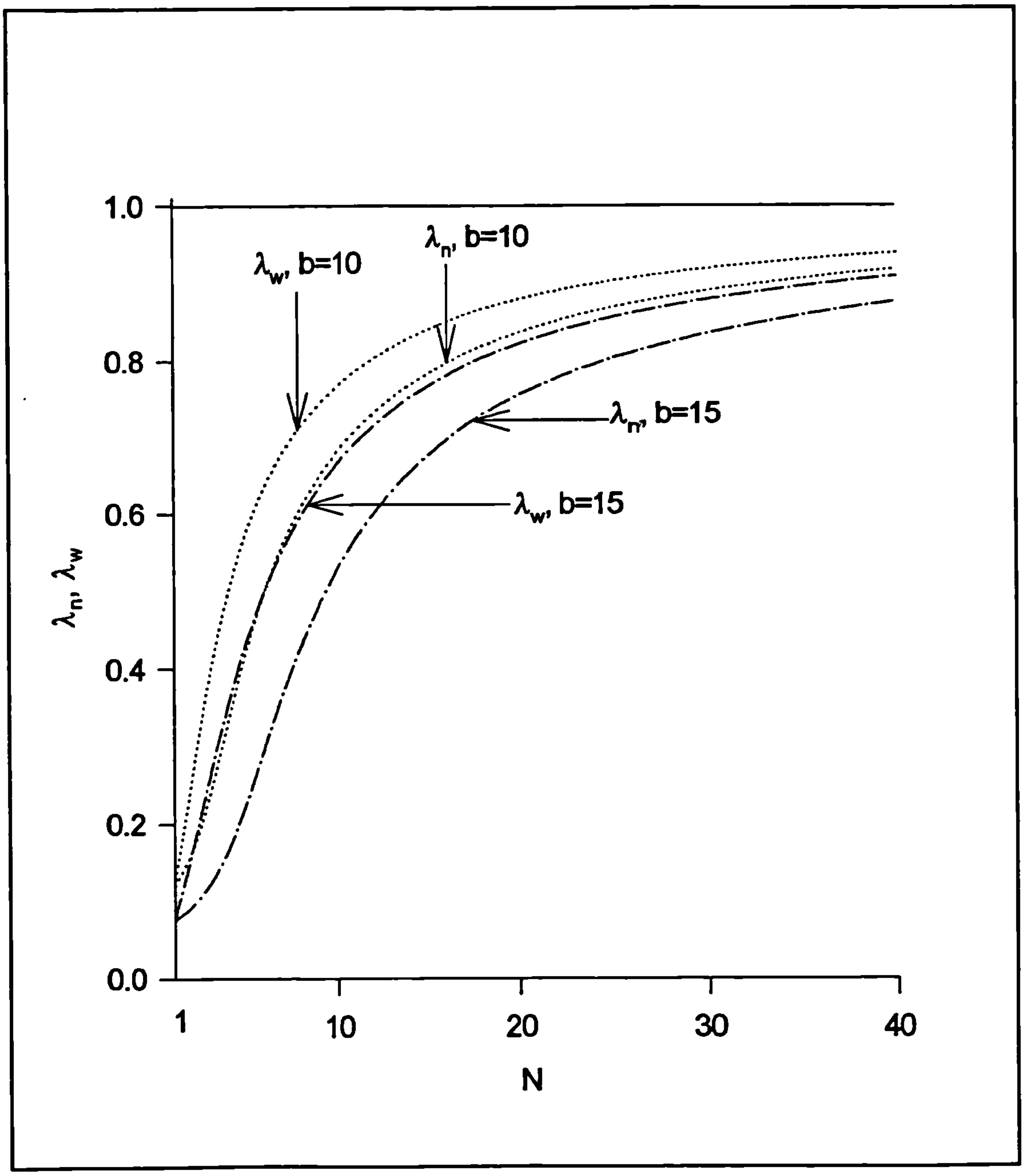
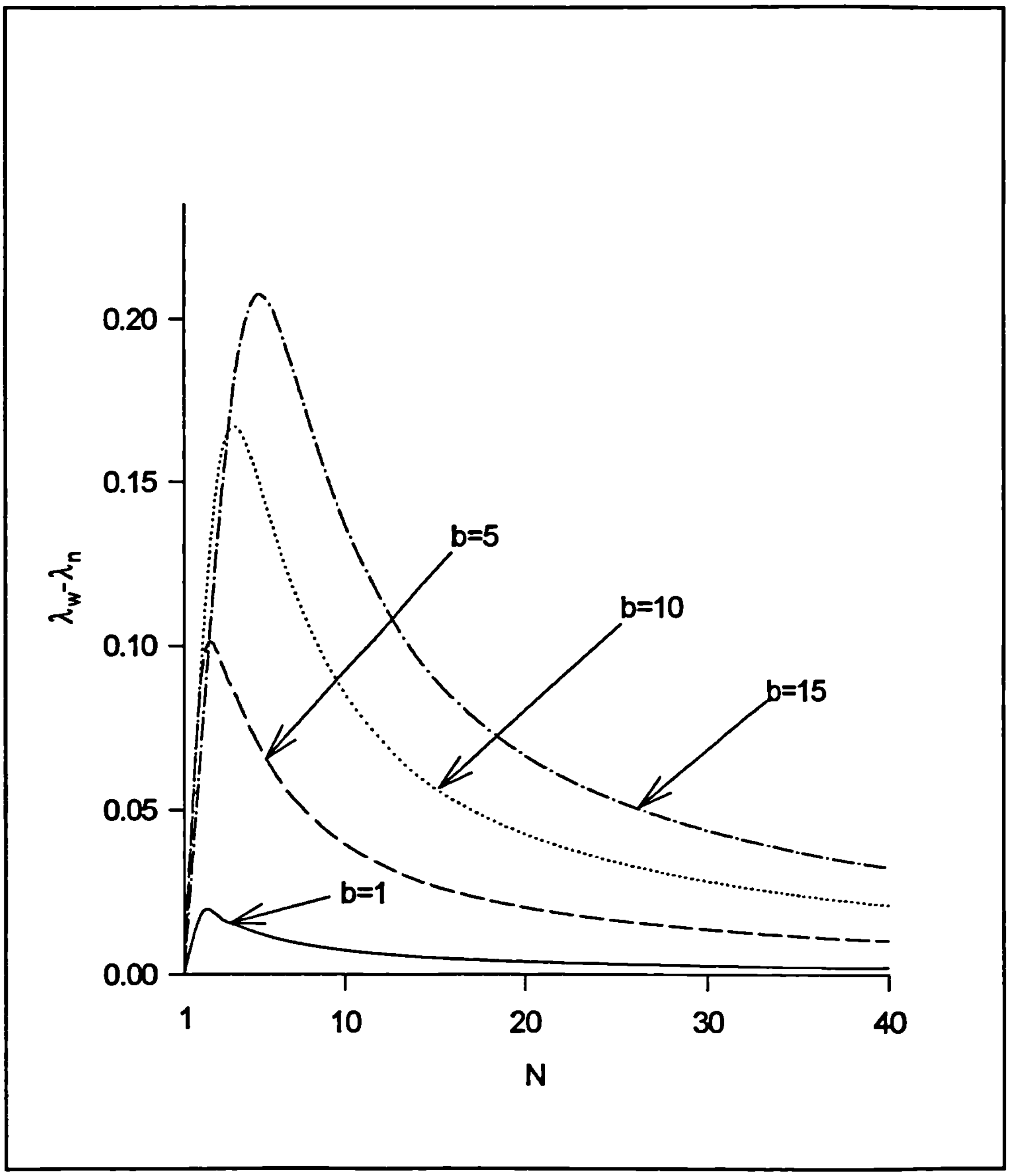


Figure 6.6

Inefficient Nash myopia as a function of the number of firms



In our model an exogenous increase in N implies a higher industry's current *aggregate* harvest. This reduces the end of period fish stock. The latter has two channels of direct influence on the value of λ_i.

First, lower levels of x imply, *ceteris paribus*, increasing reductions in each firm's marginal productivity of fishing effort. This is due to the assumption of a decreasing marginal harvesting productivity for additional fish stock units. Hence, increasing industry's *aggregate* harvests (due to a larger N) imply increasingly lower marginal profits for the representative firm. In other words, each firm's increasingly *internalizes*[28] the higher scarcity value of x as N gets larger. This implies a reduction in z_i^*. This effect reduces each Nash firm's *under*valuation of marginal changes in the industry's aggregate harvest as each firm decides on her optimal fishing effort. The latter argument helps to understand the convergent process between λ_w and λ_n, as $N \rightarrow \infty$.

But Figure 6.6 also shows an initial range of N values such that increases in N imply, *ceteris paribus*, a higher difference $\Delta > 0$. To understand this we must look at the second channel of influence that stems from exogenous reductions in x: the function of biological growth G(x).

Given that $dx/dt = G(x) = ax(1-x)$, we know that G(x) achieves its unique maximum value at $x = 1/2$. If $0 < x < 1/2$, the fish population has an increasing rate of growth $G(x) > 0$: in this range stock x has increasing marginal biological returns; if $x = 1/2$, the fish stock has constant marginal biological returns; if $1/2 < x < 1$, x has decreasing marginal biological returns.

If the exogenous reduction of x (due to a higher N) occurs at $x_0 < 1/2$, which is more probable the higher the value of N is, the resulting rate of growth G(x) will become lower. This reinforces the higher scarcity of x which results from the first channel of influence (productivity effect) described above. This result is consistent

[28] This effect is weakened by the use of harvesting technologies with constant returns in the use of the stock x, i.e., the *Schaefer* harvesting function.

with the endogenous *monotonic* reduction, for relatively high values of N, in the per unit overfishing gap $\Delta > 0$ as N increases.

However, when $x_0 > 1/2$ (which is more probable the lower the value of N is) the exogenous reduction of x, due to a larger N, will imply *higher* biological returns via a higher $G(x) > 0$. Hence, the marginal changes in G(x) will imply the opposite scarcity effect to that triggered via changes in the marginal productivity of fishing efforts. The marginal increase in G(x) will reduce the perceived scarcity of stock x. This will increase, *ceteris paribus*, each firm's fishing effort. And this will contribute to increase the *under*estimation of marginal changes in the aggregate harvest when firms use passive Nash conjectures. Given this effect, the (per unit) source of Cournot-Nash overfishing (the value gap $\Delta > 0$) can increase with a larger N, for relatively low values of N (or $x_0 > 1/2$).

In sum, in our dynamic model the net effect of an increasing number of firms, on the per unit source of Cournot-Nash overfishing ($\Delta > 0$), depends on the prevailing type of biological returns (increasing/decreasing in x) and also on the magnitude of the productivity penalties which may stem from falls in the fish stock x. Falls in x are a direct consequence of an increasing number of firms given the triggered higher *aggregate* harvest.

Let us now turn our attention to the case a dynamic harvesting fishery subject to a leader/followers competition setting.

(6.G) A Stackelberg multi-firm fishery.

Very few papers have previously considered formal comparisons between Cournot-Nash and Stackelberg multi-firm common pool fisheries. The two dynamic models reviewed in section (6.C.2), Levhari and Mirman (1980) and Dockner et al. (1989), examined only *duopoly* cases. And in the case of Dockner et al. (1989) the duopoly interaction centers on a static congestion (pecuniary) effect via the inverse demand function.

In sections (6.G) and (6.H) we compare the stationary harvesting equilibria which result from different definitions of *dynamic* Stackelberg and Cournot-Nash *multi-firm* fisheries. While maintaining the basic setting of section (6.D), we now additionally consider a Stackelberg equilibrium where a dynamic profit optimizing leading firm faces n identical Cournot-Nash followers that behave as *static optimizing* agents. The latter assumption is used as a simplifying device. In our discussion (with no congestion effects and firms' price taking behaviour) the oligopoly interactions exclusively arise from the dynamic externality that commonality of fish stocks brings about.

We examine the differences that a dynamic profit optimizing Stackelberg leader introduces with respect to multi-firm harvesting competition based on passive Nash conjectures. We contribute to the fisheries literature by formally analysing the changes in harvesting incentives, of dynamic optimizing firms using Cournot-Nash versus Stackelberg leadership conjectures, that result from increases in the number of rival firms.

This section is organized as follows. We first compare the Stackelberg equilibrium with the first best welfare solution of section (6.E) and with the dynamic Cournot-Nash multi-firm fishery of section (6.F). This analysis aims to establish unambiguous comparative results with respect to these previous cases. Then we compare the dynamic Stackelberg multi-firm fishery with three alternative benchmarks: First, with a *fully myopic* Cournot-Nash multi-firm fishery. Second, with a Cournot-Nash multi-firm fishery in which there is only *one* firm which behaves as a dynamic profit optimizing agent. This exercise aims to isolate the *pure* differential effect of Stackelberg leadership, versus the use of passive Nash conjectures, upon the stationary harvesting equilibrium. Finally, we compare the Stackelberg equilibrium with a second best welfare benchmark in which a price taking and dynamic optimizing planner, surrounded by n static optimizing Cournot-Nash firms, aims to maximize the discounted value of the intertemporal *aggregate* profits in the common pool fishery. This *social planner* cannot achieve the first best welfare solution because he can only control the fishing effort from one firm while the remaining n firms keep harvesting in a non-cooperative way. The latter exercise aims to illustrate the consequences, on the assessment of overfishing, arising from fishing regulators with only *partial* control over the fishing efforts of the industry's harvesting fleet.

(6.G.1) The Stackelberg and FMNE fisheries.

Imagine we have a dominant firm in our fishery. Assume that this implies Stackelberg leadership attributes; that is, the leader (denoted by ℓ) has the ability to credibly commit to a given effort strategy z_ℓ*. This signal is observed by the followers. The leader also knows the followers' reaction functions. Suppose that all N firms have identical harvesting productivity.

Suppose the representative Nash follower, "f", is a static profit maximizing agent ($\lambda_f=0$) and hence disregards the effect of current harvesting on future fish stock. In this case, the follower's optimal effort will be (using (F.4')):

$$z_f^* = \frac{x^*}{4w^2} \tag{G.1}$$

If all firms, including the leader, followed the effort policy (G.1), the corresponding steady state value for the fish stock (x^*) would be (using (F.8)=0, for $x^*>0$):

$$x^{*} = 1 - \frac{N}{2aw} \tag{G.2}$$

For convenience, let us call this case a "*fully myopic Nash equilibrium*" (FMNE)[29]. We will later consider this case as a benchmark to compare with the Stackelberg fishery defined above.

Notice that in the dynamic Cournot-Nash multi-firm fishery of section (6.F) the corresponding steady state value for the stock x is (using (F.8)=0):

$$x^{*} = 1 - \frac{N}{2aw}(1-\lambda_n) \tag{G.2'}$$

Hence, the stationary stock solution in an FMNE fishery will be lower than in the corresponding dynamic Cournot-Nash profit optimizing multi-firm case as long as the representative firm's marginal scarcity value λ_n be greater than zero. A *sufficient* condition for the latter is 4/3N>0 (see equation (F.11)).

- The Stackelberg leader's problem.

The dynamic profit optimizing leader's problem consists in:

$$Max_{z_t}\ V_t = \int_0^{\infty} e^{-rt}(z_t^{1/2}x^{1/2} - wz_t)dt \tag{G.3}$$

subject to

[29] Note that in this case, $x^{*}>0$ requires that $N<2aw$. Hence, for relatively high values of N, relatively low rates *a* of biological growth and/or relatively low per unit cost w of fishing effort, this type of harvesting equilibrium can imply $x^{*}=0$.

$$\dot{x} = ax(1-x) - z_\ell^{1/2}x^{1/2} - n(z_f^{1/2}x^{1/2}) \tag{G.4}$$

where z_f is given by (G.1) and $z_\ell \geq 0$, $x \geq 0$, $x(0)=x_0>0$, $w>0$, $0<r<1$; where discount rate r, price p and cost w are the same as in the welfare case.

Note that the leader can only (indirectly) affect followers' effort decision via changes in x. If the leader increases his effort, and hence his harvesting, the corresponding reduction in x will discourage followers' fishing effort. We call this process a *preemptive* strategic incentive. By using this procedure, "ℓ" can increase his market share though at the cost of an overall fall in x and, therefore, in each firm effort's marginal productivity.

The corresponding current valued Hamiltonian H_ℓ is (using also (G.1)):

$$H_\ell = z_\ell^{1/2}x^{1/2} - wz_\ell + \lambda_\ell\,[ax(1-x) - z_\ell^{1/2}x^{1/2} - \frac{nx}{2w}] \tag{G.5}$$

The first order condition $\partial H/\partial z_\ell=0$ implies the following optimal effort for the leader:

$$z_\ell^* = \frac{(1-\lambda_\ell^*)^2 x^*}{4w^2} \tag{G.6}$$

As before, $\lambda_\ell \geq 1$ implies $z_\ell^*=0$. By using the remaining first order conditions we can find the loci $\dot{x}=0$ and $\dot{\lambda}=0$:

$$G(x,\lambda_\ell) \equiv \dot{x} = x\left[a(1-x) - \frac{(1-\lambda_\ell)+n}{2w}\right] \tag{G.7}$$

which in steady state ($\dot{x}=0$) implies the following locus:

$$x = 1 - \frac{(1-\lambda_\ell)}{2aw} - \frac{n}{2aw} \tag{G.8}$$

For positive parameter values this locus always has a positive slope, and this slope is N times higher than in the welfare case. By comparing this locus with its equivalent in the welfare case, we can derive an interesting result. Rewriting (E.10'), the locus $\dot{x}=0$ in the welfare case is given by:

$$x_w^* = 1 - \frac{(1-\lambda_w^*)}{2aw} - \frac{n(1-\lambda_w^*)}{2aw} \tag{G.9}$$

Note that the steady state equilibria for the Stackelberg and the welfare cases have to fulfil (G.8) and (G.9), respectively[30]. By direct inspection of these equations we can propose:

Lemma 1:

For positive steady state values of λ^*, if $(\lambda_w^*-\lambda_\ell^*) > 0$ then necessarily $x_w^* > x_s^*$, where x_s^* denotes the steady state equilibrium value of x in the Stackelberg fishery.

Given this result, we can focus the overfishing proof on the relative values for λ_w^* and λ_ℓ^*. Given fully myopic Nash followers ($\lambda_f=0$), the stationary solution for λ_ℓ^* will correspond to the steady state solution for the scarcity value of x in the Stackelberg fishery as a whole. Denote the latter equilibrium value by λ_S.

Again from first order conditions we find that locus $\dot{\lambda}$, in this Stackelberg fishery, is given by:

$$S(x,\lambda_\ell) \equiv \dot{\lambda} = \lambda_\ell \left[r + \frac{n}{2w} - a(1-2x) \right] - \frac{(1-\lambda_\ell)^2}{4w} \tag{G.10}$$

which in steady state implies the following locus:

[30] Notice that (G.8) and (G.9) cross the x axis at the same point.

$$(x_s)^* = \left[\frac{1}{8aw}\right]\frac{(1-(\lambda_t)^*)^2}{(\lambda_t)^*} + \frac{1}{2}\left[1-(r/a)-\frac{n}{2aw}\right] \tag{G.11}$$

As in the welfare case, this locus always has a negative slope if $0<\lambda_t<1$. However, in the Stackelberg case the absolute value of this slope is N times higher than in the welfare case.

Solving (G.8) and (G.11) for λ_S we get the following positive stationary solution ($0<\lambda_S<1$):

$$\lambda_s^* = \frac{N}{2}\left[\frac{2}{3} - \frac{4Rw}{3N} + \sqrt{\left[\frac{4Rw}{3N}-\frac{2}{3}\right]^2 + \frac{4}{3N^2}}\right] \tag{G.12}$$

whereas the welfare solution is (rewriting (F.10)):

$$\lambda_w^* = \frac{1}{2}\left[\frac{2}{3} - \frac{4Rw}{3N} + \sqrt{\left[\frac{4Rw}{3N}-\frac{2}{3}\right]^2 + \frac{4}{3}}\right] \tag{G.13}$$

with $R=(r+a)$, $0\leq \lambda_i^*<1$.

Therefore, the sign of $(\lambda_W^* - \lambda_S^*)$ is given by the sign of the following expression:

$$D\left[\frac{1}{N}-1\right] + \sqrt{\left[\frac{D}{N}\right]^2 + \frac{4}{3N^2}} - \sqrt{D^2 + \frac{4}{3N^2}} \tag{G.14}$$

with

$$D = \frac{2}{3}\left[1 - \frac{2Rw}{N}\right]$$

Direct inspection of (G.14) shows that $D<0$ is a *necessary* condition for $\lambda_w^* > \lambda_S^*$, given that invariably $N\geq 2$ in the oligopoly case. Appendix 6.7 shows that

D<0 is also a *sufficient* condition in order to attain this result. This allows us to propose:

Proposition 2:

A Stackelberg fishery, with fully myopic Nash followers ($\lambda_f=0$), will tend to undervalue the true long-run scarcity value of its fish stock, that is $\lambda_w > \lambda_s$, if the following condition holds:

$$2Rw > N = n+1 \quad , \quad R = r+a \tag{G.15}$$

If this holds, then Lemma 1 ensures that the Stackelberg fishery will also maintain an inefficiently low level of fish stock in the long run; that is, $x_w^* > x_S^*$.

The intuition underlying condition (G.15) is as follows. Consider the case of higher r, a, or w. A higher value in any of these parameters would reduce the scarcity value of x. Therefore, we should expect that λ_w becomes lower. The same should occur with λ_S. But in the latter case the fall will be greater. This is due to the lower marginal cost of current harvesting implied by a lower λ value; therefore, to preempt rivals' current harvesting becomes more attractive (less costly) for each non-cooperative firm. This additional private gain from current harvesting will imply a lower private valuation for the scarcity λ value than the expected fall in the shadow value λ_w. Therefore, strategic *preemptive* incentives lead the Stackelberg fishery to inefficient overfishing in the long-run.

Will the overfishing be greater with or without the non-fully myopic Stackelberg leader?

It must be borne in mind that a fully myopic Nash equilibrium (FMNE), with all N firms harvesting in fully myopic fashion, implies the long-run fish stock given by (G.2). On comparing this stock to the corresponding Stackelberg steady state value generated at locus $\dot{x}=0$ in (G.8), we can see that as long as $\lambda_l^*>0$ the Stackelberg fishery will maintain a higher x^*. Therefore:

Proposition 3.

The introduction of a non-fully myopic Stackelberg leader will necessarily reduce the level of overfishing compared with an FMNE multi-firm fishery.

(6.G.2) The dynamic optimizing Cournot-Nash fishery as a benchmark.

How much of the Stackelberg overfishing improvement (versus the FMNE case) stated in Proposition 3 is due to the dynamic optimizing behaviour of the leading firm and how much due to the strategic preemptive power of the Stackelberg leader? To explore this issue we first compare the previous Stackelberg equilibrium with the dynamic optimizing Cournot Nash fishery of section (6.F). Afterwards, we compare the Stackelberg solution with a Cournot-Nash multi-firm fishery in which only one firm is a dynamic profit optimizing agent. Finally, we consider as a benchmark a second best welfare solution such that a dynamic optimizing social planner has control over only one firm's fishing effort, with all the remaining n firms being Cournot-Nash static optimizing agents.

With the dynamic Cournot-Nash fishery of section (6.F) as a yardstick for comparison, we will show that our Stackelberg fishery, with only one dynamic optimizing firm (the leader), invariably implies lower stationary values for the fish stock x, for any $N>1$. When the benchmark is a Cournot-Nash fishery with only one firm behaving as a dynamic profit optimizer, we will obtain an identical stationary solution to the Stackelberg equilibrium. Finally, in terms of the second best welfare yardstick, our Stackelberg fishery will invariably imply overfishing for any $N>1$.

Let us start by comparing the dynamic Cournot-Nash fishery of section (6.F) with the previous Stackelberg solution. Looking at the equations that describe the corresponding locus $\dot{x}=0$ in each case, and using a similar logic to Lemma 1, we can deduce that as long as $\lambda_n \geq \lambda_S$ the resulting stationary solutions will be such that $x_n > x_S$. If, on the contrary, $\lambda_n < \lambda_S$, the ranking between the stationary solutions x_n and x_S is not obvious on a *an priori* basis. Let us perform a numerical simulation to clarify this issue.

We can obtain numerical solutions for both stationary equilibria as functions of parameters N and $b \equiv 4(r+a)w > 0$[31]. Let us consider the arbitrary fixed values of $w=0.8$, $a=4$ and make parameter b to vary as a function of r, with $r=\{0;\ 1/2;\ 1\}$. Higher values of r represent, *ceteris paribus*, an exogenous lower scarcity value of the marginal unit of investment at x[32].

Simulation results, as functions of N and r values, are shown in Figures 6.7 and 6.8. From the former we can deduce that the function $\lambda_S=\lambda_S(N)$ is strictly convex in N. Given the concave behaviour of function $\lambda_n=\lambda_n(N)$ we see that, for the simulated parameter values, the functions cross each other[33]. While the solution λ_n monotonically converges to the value of 1 as $N \rightarrow \infty$, the solution λ_S exceeds 1 for a finite N. The latter value of N decreases as the exogenous scarcity of x increases (for instance, due to a lower discount rate). Recall that with $\lambda_S \geq 1$, the Stackelberg leader's optimal policy is to stop fishing (equation G.6).

Hence, for $\lambda_S \geq 1$ the Stackelberg fishery transforms itself into a Cournot Nash fishery with n fully myopic firms. The resulting stationary fish stock solutions are shown in Figure 6.8.

We can observe that, for any $N>1$, invariably $x_n > x_S$. Hence, we can deduce that N dynamic optimizing Cournot Nash harvesters generate less overfishing than the case of a dynamic optimizing Stackelberg leader who is surrounded by (N-1) static optimizing Cournot-Nash followers. In the latter case, as the number of fully myopic followers starts to increase, the Stackelberg leader will inevitably leave the

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[31] Solutions λ_n and λ_S are given by (F.11) and (G.12), respectively. We then use the corresponding loci $\dot{x}=0$ to obtain x_n and x_S.

[32] Notice that with these parameter values we are assuming b values between 13 and 16. Therefore, the solution for λ_n must be similar to those shown in Figure 6.5.

[33] A lower value for a and/or w implies that both curves move upwards (in a Northwest direction). With this type of parametric changes we *can* obtain that invariably $\lambda_S > \lambda_n$, for any given value of $N>1$. For example, this occurs for $a=2$, $w=1/2$ and $r=1/2$. However, the convex behaviour of $\lambda_S=\lambda(N)$ and the concave behaviour of $\lambda_n=\lambda(N)$ remain unchanged.

fishery ($\lambda_S \geq 1$). Subsequently, the fish population will be extinguished for a finite number N of firms[34]. Higher time discounting accelerates this process[35]. What is the intuition behind this result?

In the Stackelberg fishery studied, only one firm (the leader) considers the fish stock's net growth. In the dynamic Cournot-Nash fishery of section (6.F), all N firms make effort decisions in this way. Therefore, as the number of rival firms increases, the Stackelberg leader internalizes a higher increase in rivals' total current harvesting than the increase perceived by any individual firm in the dynamic Cournot-Nash case. This occurs because a dynamic profit optimizing firm will choose, *ceteris paribus*, a lower current fishing effort than a fully myopic harvester, for a given level of intertemporal availability of x. This is the reason why, for given values of a, w and r, λ_S increases faster than λ_n does, as N gets higher. The same reason explains why in the Stackelberg fishery x becomes extinguished for a finite N, while in the dynamic Cournot-Nash fishery x monotonically decreases but remains positive for finite N values[36].

The dynamic Cournot-Nash fishery of section (6.F) has the disadvantage, as a benchmark for our Stackelberg multi-firm fishery, that it assumes that *all* N firms are dynamic profit optimizing agents. To isolate the net effect stemming from the feature of Stackelberg leadership, let us now compare the Stackelberg fishery with

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[34] Recall than in the resulting *FMNE* fishery the fish stock is extinguished if N > 2aw (see equation (G.2)). Once the dynamic optimizing leader decides to leave the fishery, the condition for extinction is fulfiled with N=n+1=7 (with a=4 and w=0.8).

[35] The simulation results with r=0 do not change the qualitative pattern of influence of increases in r upon the stationary solutions for x.

[36] What about the possibility of extinction in the dynamic Cournot-Nash fishery of section (6.F)? Consider equation (G.2´): the stationary stock x_n^* will be positive as long as $(1-\lambda_n)<(2aw)/N$. The simulation results in Figure 6.8 show that in this type of fishery the stock x monotonically decreases as N gets bigger. But λ_n^* increases with higher N and this reduces the representative firm's fishing effort. When $N\rightarrow\infty$, $\lambda_n^*\rightarrow 1$ and $z_i^*\rightarrow 0$. However, taking the limit of the condition above for $N\rightarrow\infty$, we can deduce that x=0 in this limit case.

a case where all N firms use passive Cournot-Nash conjectures, but there is one firm which is a dynamic profit optimizing agent (as in our Stackelberg fishery).

(6.G.3) A Cournot-Nash fishery with only one dynamic optimizing harvester. Denote the single Cournot-Nash dynamic profit optimizer as firm 1. The remaining n static optimizing Cournot Nash firms will choose the representative fishing effort z_i given by equation (G.1). Firm 1 will maximize, in each time period, the following Hamiltonian function:

$$H_1=(1-\lambda_1)z_1^{1/2}x^{1/2}-wz_1+\lambda_1\left(ax(1-x)-nz_i^{1/2}x^{1/2}\right) \tag{G.16}$$

with λ_1 denoting firm 1's internalized scarcity value for x. Using $\partial H_1/\partial z_1=0$, we obtain that firm 1's optimal fishing effort is given by an effort rule identical to equation (G.6).

Following identical steps as in previous sections to derive the loci $\dot{x}=0$ and $\dot{\lambda}=0$, we obtain that the former corresponds in this fishery to:

$$x=1-\frac{(1-\lambda_1)}{2aw}-\frac{n}{2aw} \tag{G.17}$$

Notice that this is a function identical to the corresponding locus $\dot{x}=0$ in the Stackelberg fishery (equation G.8). Similarly, by setting $\dot{\lambda}=[r\lambda_1-\partial H_1^*/\partial x]=0$, where H_1^* considers the optimal effort policies z_1^* and z_i^*, we obtain that:

$$S(x,\lambda_1)\equiv\dot{\lambda}=\lambda_1\left[r+\frac{n}{2w}-a(1-2x)\right]-\frac{(1-\lambda)^2}{4w} \tag{G.18}$$

We again obtain an equation identical to the corresponding locus in the Stackelberg fishery (equation G.10). Therefore, the corresponding stationary equilibrium of the current Cournot-Nash fishery will be identical to the steady state solution in the Stackelberg fishery.

The latter result implies that in the basic dynamic model of this chapter (section 6.D) it makes no difference if a single dynamic profit optimizing firm, who competes in harvesting with n Cournot-Nash static profit optimizing rival firms, has Stackelberg leadership attributes or not. Hence, the improvement in the overfishing problem that Proposition 3 refers to is *exclusively* due to the introduction of a harvester who internalizes the intertemporal availability of x as a binding constraint in his profit optimization problem. Which is the intuition behind this result?

The key point is that in our dynamic model, without technological congestion effects and with price taking firms, the static optimizing harvesters use fishing effort decision rules which are independent of rivals' effort (equation G.1). This means that a harvester who has a *first mover* advantage, as the case of the Stackelberg leader, cannot *directly* affect his rivals' actions. Because there is no congestion (via pecuniary or technological effects) the Cournot-Nash static optimizing firms' fishing effort depends only on the stock and is not directly affected by any other firm's effort. In the duopoly Stackelberg fishery of Dockner et al. (1989) the leader directly affects the follower's fishing effort via the induced effect on the demand price of harvests. In the duopoly Stackelberg case of Levhari and Mirman (1980), the Stackelberg leader directly affects the follower's actions because both players are dynamic profit optimizing agents with objective functions depending on the current fish stock level.

Hence, in our Stackelberg model the leadership attribute merely implies that the leading firm recognizes the stock constraint (G.4). This is the reason why in the Cournot-Nash fishery of this subsection the stationary equilibrium is equivalent to the Stackelberg solution.

Our Stackelberg leader's single channel of influence on followers' actions is the effect of his own harvesting upon x. He knows that followers pursue closed-loop fishing effort policies. Therefore, the leader will try to harvest x as fast as he can, provided that it is profitable for him to do so. In this cost/benefit analysis, the dynamic optimizing leader internalizes that a higher current fishing effort implies, *ceteris paribus*, a lower x in the next period. And he knows that this implies a harvesting productivity penalty on his own future fishing efforts.

In the current subsection, the single dynamic profit optimizing Cournot-Nash firm has an identical incentive structure to the Stackelberg leader's one. This Cournot-Nash firm makes the *conjecture* that his rivals' fishing effort remains unchanged when he marginally varies his own effort. And this is what precisely occurs, as the Stackelberg leader knows. The dynamic optimizing Cournot-Nash firm also knows, as the Stackelberg leader does, that his rivals take effort decisions based on equation (G.1). Therefore, he will also want to harvest x as quick as he can in a profitable way. His cost/benefit analysis will also internalize the intertemporal availability of x as a binding constraint.

To close this analysis, let us finally consider how a (second best) welfare planner would decide his harvesting strategy provided that: (i) he can only control the fishing effort of one harvesting firm, and (ii) all the remaining n harvesters are again Cournot-Nash static profit optimizing players.

(6.G.4) A second best welfare case.

Denote this case by W2. The planner's objective is identical to function V in (E.1). The difference is that he can only control one harvesting firm, call it firm 1, while remaining n firms are Cournot-Nash static profit optimizing agents, each of them with a representative fishing effort z_i given by equation (G.1). The difference in this section compared with the previous oligopoly equilibria is given by the planner's aim which consists in maximizing the discounted value of the industry's *aggregate* intertemporal profits, subject to the *restricted* instruments (relative to the first best welfare case) under his control.

At each time period, the planner maximizes (by choosing z_1) the following current valued Hamiltonian function:

$$H_{W2}=(1-\lambda_{W2})x^{1/2}(z_1^{1/2}+nz_i^{1/2})-w(z_1+nz_i)+\lambda_{W2}ax(1-x) \tag{G.19}$$

with λ_{W2} denoting the shadow price assigned by the planner to the marginal unit of investment at x.

Using $\partial H_{W2}/\partial z_1=0$, the planner's optimal effort policy is given by a function identical to equation (G.6). This means that if $\lambda_{W2}\geq 1$, then the planner's optimal effort policy is to set $z_1=0$. In this case, the common pool fishery becomes a Cournot-Nash equilibrium with n static optimizing firms. In this FMNE case, x becomes extinguished when n > 2aw (see equation G.2). Let us explore whether or not the second best welfare planner decides to stop firm 1's harvesting, for a finite number N of firms.

As previously explained, we first obtain loci $\dot{x}=0$ and $\dot{\lambda}=0$ and by combining them we then derive the stationary equilibrium $W2\equiv\{x_{W2}^*, \lambda_{W2}^*\}$. Locus $\dot{x}=0$ is now given by a function identical to equation (G.8); whereas locus $\dot{\lambda}=[r\lambda_{W2}-\partial H_{W2}^*/\partial x]=0$ corresponds to:

$$x=\frac{1}{8aw}\frac{(1-\lambda_{W2})(N-\lambda_{W2})}{\lambda_{W2}}+\frac{1-(r/a)}{2} \tag{G.20}$$

Notice that for $\lambda_{W2}\geq 1$, this locus corresponds to a vertical line $x=[1-(r/a)]/2$ in the space (λ,x). As $\lambda_{W2}\rightarrow 0$, (G.20) implies $x\rightarrow\infty$ (see Figure 6.10).

By combining equations $\dot{\lambda}=0$ and $\dot{x}=0$ we obtain the stationary solution for the planner's scarcity value λ_{W2}:

$$\lambda_{W2}=\frac{1}{2}\left[N-\frac{(1+4Rw)}{3}+\sqrt{\frac{4N}{3}+\left[N-\frac{(1+4Rw)}{3}\right]^2}\right] \tag{G.21}$$

Comparing this solution with the dynamic optimizing Cournot-Nash fishery's stationary solution for the scarcity value of x (given by equation (F.11)), we have $\lambda_{W2}=N\lambda_n$. Looking at solution λ_S (equation (G.12) we can also verify that $\lambda_{W2}>\lambda_S$, for any $N>1$. Given the convex behaviour of $\lambda_S=\lambda_S(N)$, the previous result means that $\lambda_{W2}=\lambda_{W2}(N)$ will also be a convex function. A numerical simulation exercise confirms this result. Figure 6.9 illustrates[37].

The latter result means that the second best welfare planner internalizes, relative to the dynamic optimizing Stackelberg leader, more of the increasing scarcity of population x as N becomes higher (due to the industry's higher total current harvesting). Therefore, the planner reduces firm 1's fishing effort faster than the reductions in the Stackelberg leader's own fishing effort as N increases. Figure 6.9 shows that the welfare planner decides to stop his own fishing (when $\lambda_{W2}\geq 1$) for a lower N than the number of firms that triggers the shut down of the private leader's harvesting actions. Which are the consequences in terms of the stationary solutions for x?

First, given that the locus $\dot{x}=0$ is the same in the Stackelberg and W2 solutions, we can deduce that if $\lambda_{W2}^*>\lambda_S^*$, then necessarily $x_{W2}^*>x_S^*$ (see equations G.8-G.17), as long as $x_{W2}^*>0$. Notice that both λ_{W2}^* and λ_S^* eventually becomes greater than one, for a finite N. Hence, in both cases the *single* dynamic optimizing decision maker eventually stops his own harvesting, leaving behind him a FMNE fishery which extinguishes the population x if the number n of fully myopic harvesters is such that $n>2aw$ (see equation G.2).

The simulation results plotted in Figure 6.8 confirm these deductions. Figure 6.8 plots the stationary solutions x_n (dynamic Cournot-Nash case), x_{W2} and x_S as functions of the total number N of firms and for two discount rates $r=\{1/2;1\}$. We observe the expected Stackelberg overfishing with respect to the second best welfare benchmark for $N>1$, until x_{W2} becomes extinguished for a finite N.

Before the planner decides to set $z_1=0$, Figure 6.8 shows a full equivalence between the stationary solutions x_n and x_{W2}. We can confirm the generality of this

[37] This simulation assumes identical parameter values to those in section (6.G.2); that is, $w=0.8$, $a=4$ and two values for the discount rate $r=\{1/2;1\}$.

result by looking at the corresponding loci $\dot{x}=0$ in both equilibrium concepts. In the case of the W2 solution, we can write this locus as (see equation G.8):

$$x_{W2} = 1 - \frac{(N-\lambda_{W2})}{2aw} \tag{G.22}$$

while in the case of the dynamic Cournot-Nash fishery this locus corresponds to (rewriting the equivalence to equation (E.10') for the Cournot-Nash equilibrium):

$$x_n = 1 - \frac{N(1-\lambda_n)}{2aw} \tag{G.23}$$

From (G.22)-(G.23) we infer that the stationary solutions have $x_n=x_{W2}$ as long as $\lambda_{W2}=N\lambda_n$. And this was precisely the relationship deduced above[38]. However, this is only valid as long as $\lambda_{W2}<1$. Otherwise, given that $\lambda_n<1$ for finite N, we have $x_n>x_{W2}$, because when $\lambda_{W2}\geq 1$, x_{W2} begins to be determined by an FMNE fishery. Figure 6.8 illustrates the latter argument for N values such that $z_1=0$ (or $\lambda_{W2}\geq 1$).

As a summary of our findings, figure 6.10 plots all the different stationary equilibria studied in sections (6.E) to (6.G.4). The plotted curves have been obtained from a numerical simulation exercise, for the following parameter values: N=4; r=1/2; a=4 and w=1. These parameter values ensure that the corresponding stationary solutions for x are positive in all cases studied, while the different stationary solutions for λ remain within the interval (0,1). The first best and second best welfare solutions are denoted by W and W2 respectively; the dynamic Cournot-Nash equilibrium is denoted by N; the Stackelberg case by S and the fully myopic Nash equilibrium by M.

[38] It is not clear how or whether this result generalizes to less specific modelling settings.

Figure 6.7

Scarcity values of the fish stock: Stackelberg and Cournot-Nash cases

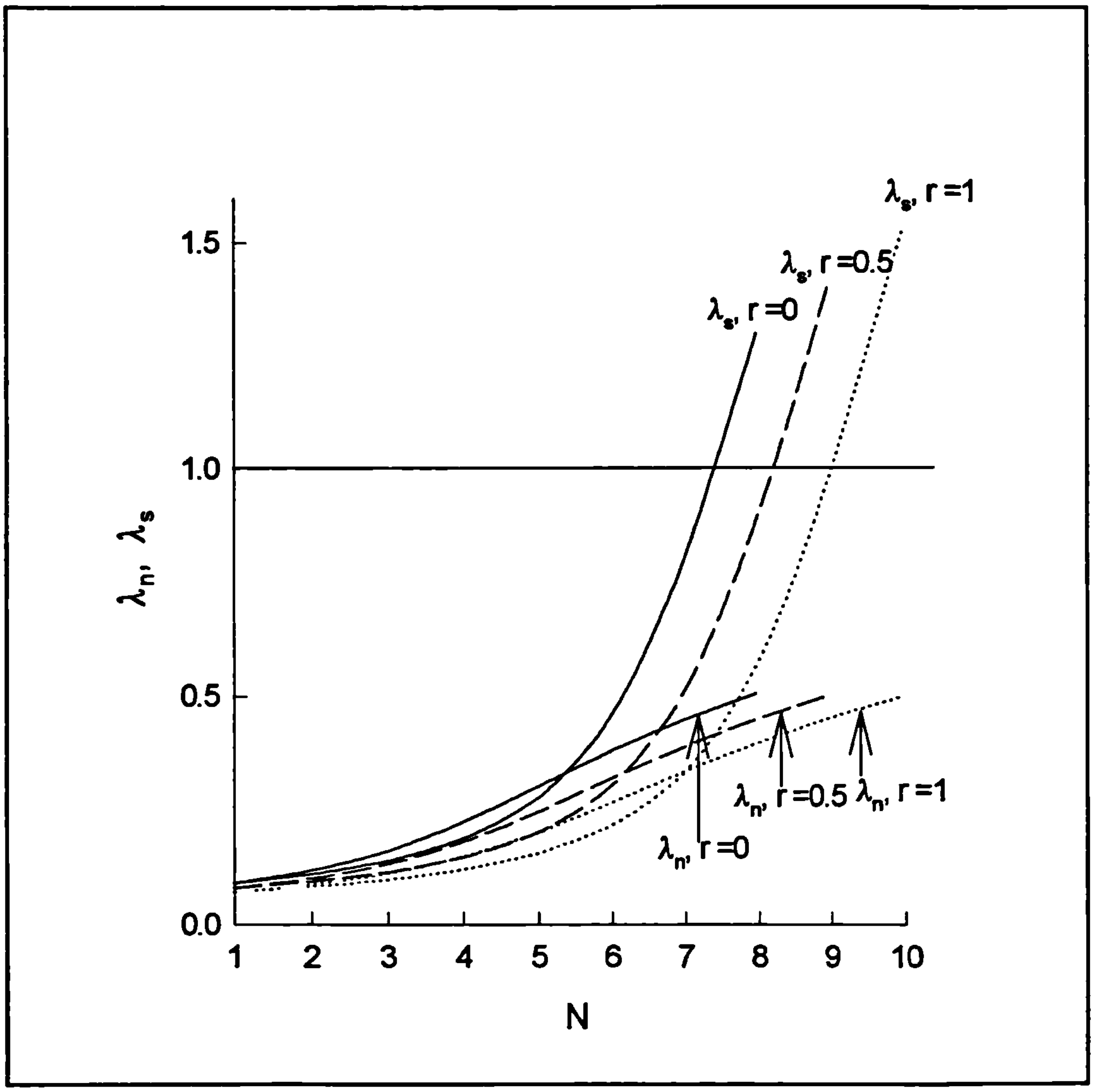


Figure 6.8

Steady State stock levels: Stackelberg, Cournot-Nash and second best Welfare cases

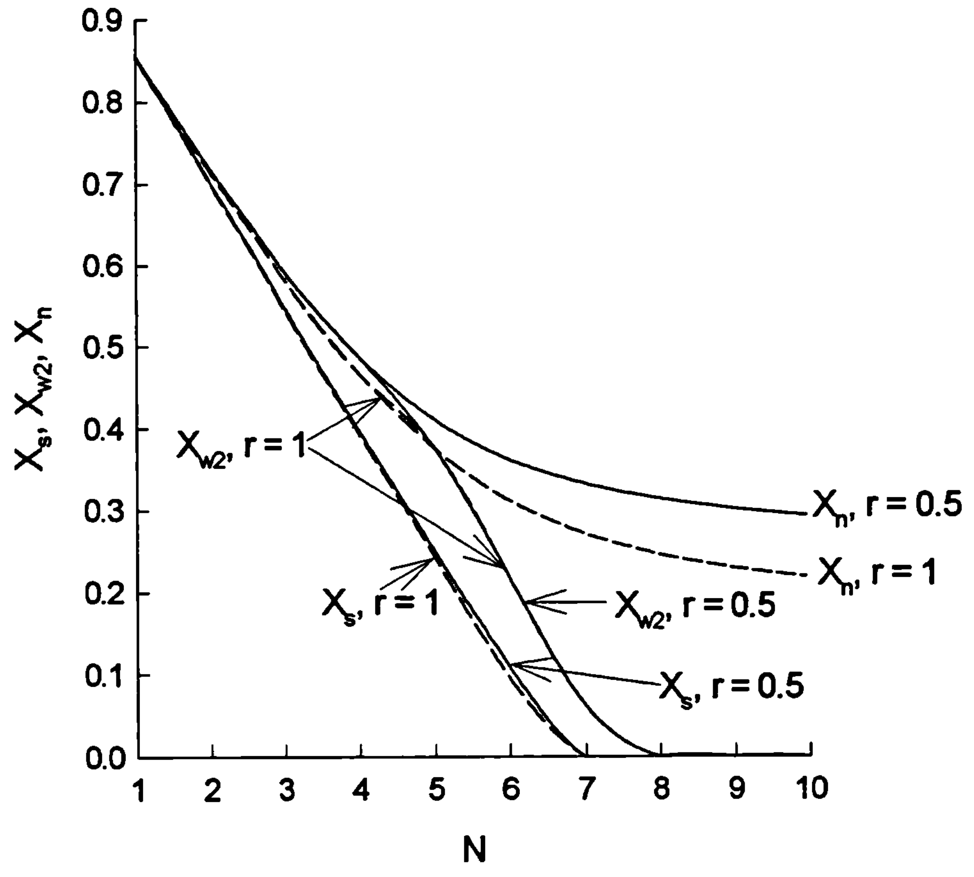


Figure 6.9

Scarcity values of the fish stock: Stackelberg and second best Welfare cases

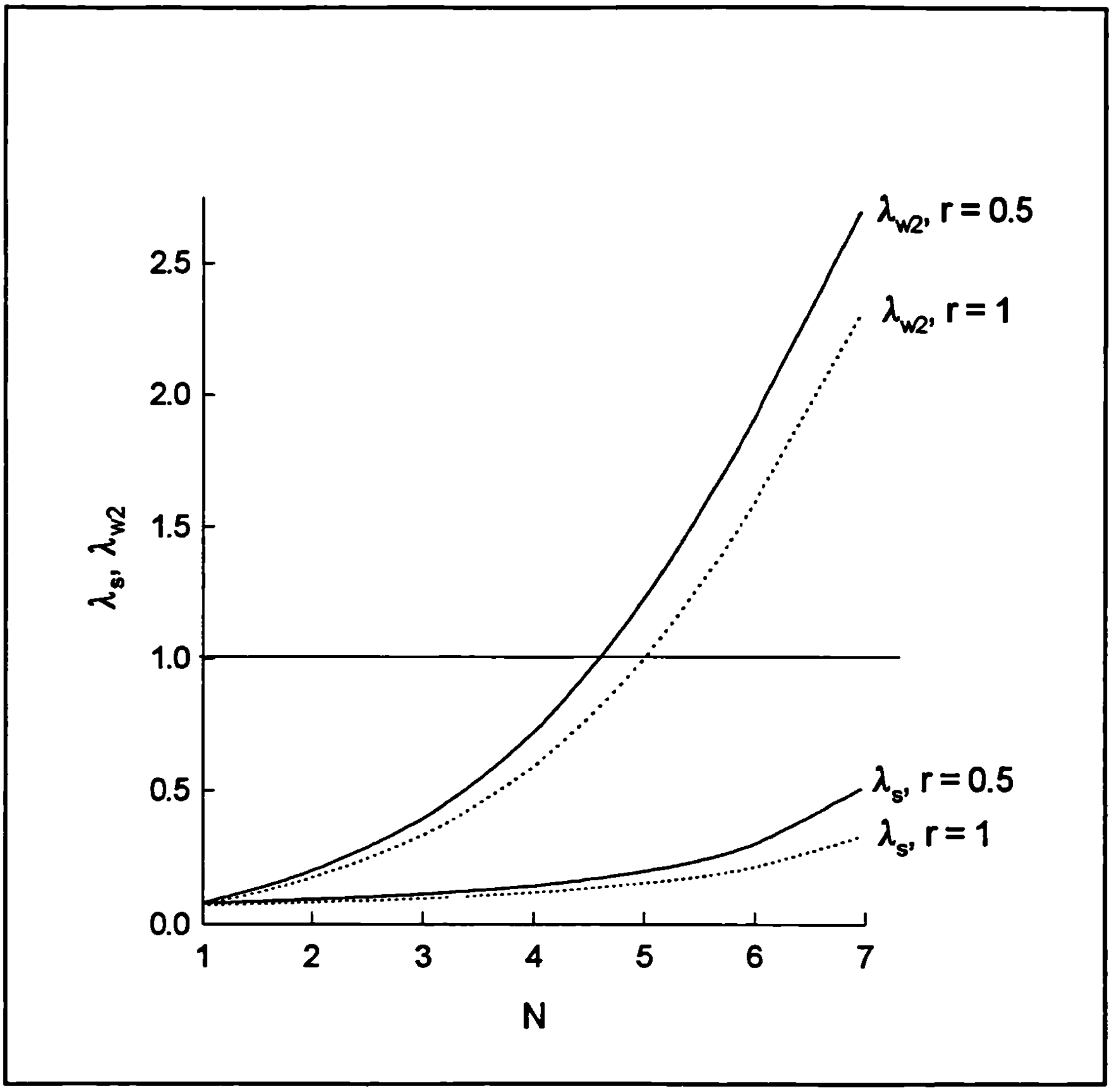
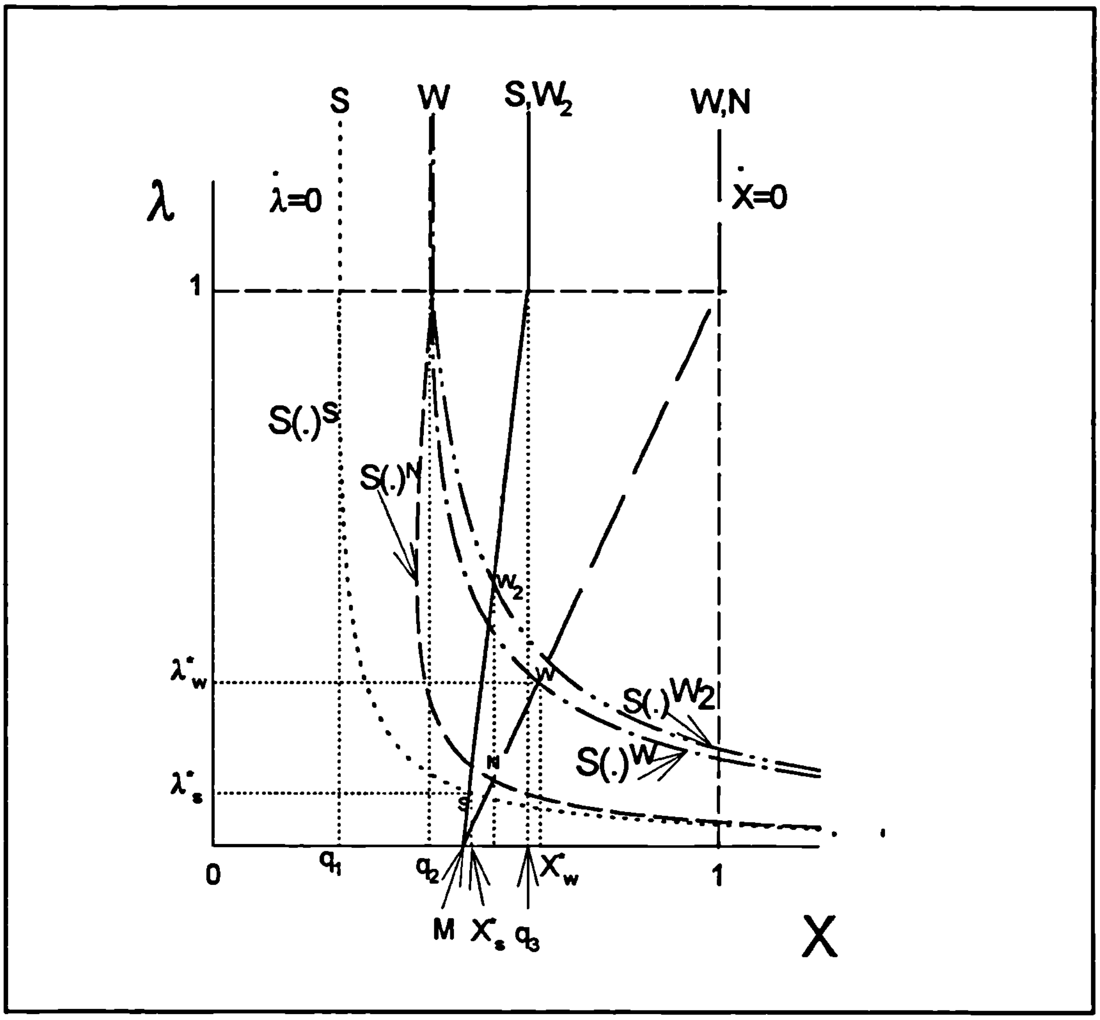


Figure 6.10

Stackelberg, Welfare and Cournot-Nash steady states



where:

$$q_1=\frac{1}{2}\left[1-(r/a)-\frac{n}{2aw}\right]$$

$$q_2=\frac{1}{2}[1-(r/a)]$$

$$q_3=1-\frac{n}{2aw}$$

(6.H) A dynamic profit optimizing Stackelberg leader with productivity advantages.

In this section we examine the implications of the *single* dynamic profit optimizing Stackelberg leader being more productive than the followers. On the one hand, this productivity advantage makes more plausible that the dynamic optimizer be the Stackelberg leader. On the other hand, its allows us to examine how the leader's harvesting incentives change with variations in his relative productivity advantage. As expected, an increase in the leader's productivity advantage will imply a higher optimal effort for him. However, if the followers' productivity *increases* the leader will not engage in a harvesting war; instead, he will adjust his own harvesting downwards. The reason behind this result is the dynamic optimizing behaviour of the leading firm.

For the sake of simplicity, we compare in this section the resulting Stackelberg equilibrium with the case of an FMNE fishery. We recalculate the corresponding *first best* welfare stationary solution in order to discuss overfishing results.

Let us suppose the harvesting technology of firm i is now given by:

$$h_i = d_i z_i^{1/2} x^{1/2} \tag{H.1}$$

where $0 \leq d_i \leq 1$.

Define $d_\ell = 1$ for the leader and $d_f \leq 1$ for follower f's technology; therefore, a lower d_f implies a greater leader's productivity advantage over the followers. Let us retain the assumption that the n follower firms are identical: $d_f = d$ denotes the representative follower's scaling productivity.

(6.H.1) A more general first best welfare solution.

In order to deal with efficiency considerations, we need to recalculate our welfare benchmark. In fact, under the new conditions the social planner must choose optimal efforts for the leader (z_t) and the representative follower (z_f). The planner's problem consists in:

$$Max_{z_t, z_f}\ V = \int_0^{\infty} e^{-rt}\left(z_t^{1/2}x^{1/2} + ndz_f^{1/2}x^{1/2} - w[z_t + nz_f]\right)dt \tag{H.2}$$

subject to

$$\dot{x} = ax(1-x) - z_t^{1/2}x^{1/2} - n(dz_f^{1/2}x^{1/2}) \tag{H.3}$$

with $x > 0$ and non-negative fishing efforts. The signs and values of the parameters remain unchanged.

Accordingly, the corresponding current valued Hamiltonian H is:

$$H = x^{1/2}[z_t^{1/2} + ndz_f^{1/2}] - w(z_t + nz_f) + \lambda_w\left(ax(1-x) - x^{1/2}[z_t^{1/2} + ndz_f^{1/2}]\right) \tag{H.4}$$

The first order conditions for welfare maximizing optimal effort levels z_t^* and z_f^* imply:

TABLE 6.3

Leader's effort (z_t^*)	$\frac{(1-\lambda_w)^2 x^*}{4w^2}$	(H.5)
Follower's effort (z_f^*)	$\frac{d^2(1-\lambda_w)^2 x^*}{4w^2}$	(H.6)
Total optimal effort (z_w^*)	$\frac{(1-\lambda_w)^2 x^*}{4w^2}(1 + nd^2)$	(H.7)

By using these results and the remaining first order conditions (see previous sections), we obtain the two loci that define the steady state equilibrium. In fact, $\dot{x}=0$ is described by:

$$x^{*} = 1 - \frac{(1-\lambda_{w})}{2aw}M \quad , \quad M=(1+nd^{2}) \tag{H.8}$$

whereas $\dot{\lambda}=0$ is given by:

$$x^{*} = \left[\frac{M}{8aw}\right]\frac{(1-(\lambda_{w})^{*})^{2}}{(\lambda_{w})^{*}} + \frac{1}{2}\big(1-(r/a)\big) \tag{H.9}$$

(H.8) and (H.9) imply the following steady state optimal solution for the shadow price of x:

$$\lambda_{w}^{*} = \frac{1}{2}\left[\frac{2}{3} - \frac{4Rw}{3M} + \sqrt{\left(\frac{4Rw}{3M} - \frac{2}{3}\right)^{2} + \frac{4}{3}}\right] \tag{H.10}$$

where M is given in (H.8) and R=(r+a). Note that the welfare solution (G.13) is a special case of (H.10)

We can obtain from (H.10) that $(\partial\lambda_{w})/(\partial d)>0$ (see Appendix 6.8); that is, the more productive the n smaller follower firms, the higher the shadow price for x must be. The reason for this is the increasing demand on x generated by firms with higher productivity. The impact on x^{*} is not obvious on an *a priori* basis (see equation (H.8)); however, it can be proved that the long-run equilibrium for x becomes smaller as firms' productivity increases, *ceteris paribus* (see Appendix 6.9).

(6.H.2) An FMNE fishery.

Let us now consider a non-cooperative FMNE with all N firms behaving in a fully myopic Cournot-Nash fashion. Hence the representative firm i has an equilibrium scarcity value for x such that $\lambda_i=0$. Bear in mind that this section assumes the existence of one firm with higher productivity than her rivals. Denote this firm by ℓ and her fully myopic Cournot-Nash equilibrium fishing effort by z_ℓ^*. Similarly, denote the representative Cournot-Nash firm of the remaining n symmetric rival firms by "f", each with a scaling productivity parameter $d_f=d\leq 1$.

The FMNE assumption implies the following optimal effort level for both firm ℓ and the representative firm f:

$$z_f^* = \frac{d^2x^*}{4w^2} \tag{H.11}$$

$$z_\ell^* = \frac{x^*}{4w^2} \tag{H.12}$$

Given this, the resulting steady state equilibrium x^* for the FMNE case is:

$$x^* = 1-\frac{M}{2aw} \quad , \quad with\ M=1+nd^2 \tag{H.13}$$

Notice that $x^*>0$ if and only if $M<2aw$. Therefore, a stationary equilibrium such that $x^*\to 0$ could occur the lower the rate a of biological growth and/or the per unit cost w of fishing effort are, and/or the higher the number and productivity of the firms with access to the fish stock become.

(6.H.3) The Stackelberg fishery.

Let us now introduce a dynamic profit optimizing Stackelberg leader. Let us retain the assumption that the follower firms are identical and fully myopic in their harvesting behaviour. In this case, the leader's optimization problem is to maximize at each time period the following Hamiltonian:

$$H_t = (1-\lambda_t)z_t^{1/2}x^{1/2} - wz_t + \lambda_t\,[ax(1-x) - \frac{nd^2x}{2w}] \tag{H.14}$$

that considers the followers' effort policy given by (H.11), and from which the leader decides his optimal effort which once again corresponds to (G.6).

The remaining first order conditions imply the locus $\dot{x}=0$ that is given by the following equation:

$$x^* = 1 - \frac{(1-\lambda_t^*)}{2aw} - \frac{d^2n}{2aw} \tag{H.15}$$

Comparing (H.15) and (H.8), we see that Lemma 1 is still valid in this more general framework. Therefore, we concentrate our attention on the solutions for λ.

The locus $\dot{\lambda}=0$ in the Stackelberg fishery is now given by:

$$x_t^* = \left[\frac{1}{8aw}\right]\frac{(1-\lambda_t^*)^2}{\lambda_t^*} + \frac{1}{2}\left[1 - (r/a) - \frac{nd^2}{2aw}\right] \tag{H.16}$$

Using (H.15) and (H.16) we obtain the Stackelberg value for marginal investment in x:

$$\lambda_s^* = \lambda_t^* = \frac{M}{2}\left[\frac{2}{3} - \frac{4Rw}{3M} + \sqrt{\left[\frac{4Rw}{3M} - \frac{2}{3}\right]^2 + \frac{4}{3M^2}}\,\right] \tag{H.17}$$

with $M = (1+nd^2)$ and $R = (r+a)$.

Figure 6.11 shows two steady state solutions for the Stackelberg fishery. We can see that x_s^* increases if the followers' productivity falls. It is possible to show that $\partial x_s^*/\partial d < 0$. Similarly, using (H.17) it is possible to prove that invariably $\partial\lambda_t^*/\partial d > 0$. Given both results, we also know that $\partial z_t^*/\partial d < 0$ (see equation G.6).

Figure 6.12 shows the steady state equilibria for the first best welfare benchmark: as the followers' productivity falls from $d=1$ and the steady state solution moves from W_0 to W_1, λ_w^* will also fall. In other words, we have that $\partial\lambda_w^*/\partial d>0$.

These results imply:

(a) As the followers' productivity changes, the Stackelberg leader will adjust his scarcity value of x in the same direction as the welfare planner does. For example, if the followers' productivity increases the leader will realize the stronger demand pressures on x and, hence, he will adjust the steady state value of λ_ℓ^* upwards.

(b) In the Stackelberg fishery, the dynamic optimizing leader's effort policy will *run counter to* the changes in the followers' fishing efforts that arise from changes in their productivities. If the followers' productivity *decreases* (and hence their optimal efforts), the leader will increase his own fishing effort and, as a direct effect, his share in the common pool resource. However, if the followers' productivity *increases* the leader will not engage in a "harvesting war"; instead, he will adjust his own harvesting downwards.

The source of the latter result is the positive value of λ_ℓ^*. This means that the leader assigns a positive value to marginal investments in x; in other words, future catches have a positive value within the frame of current decisions on fishing effort. Therefore, if the rivals' productivity falls, the leader will take advantage of this in terms of current harvesting, but also considering the future additional harvesting that he can obtain in the next time periods. If the rivals' productivity increases the leader will realize the stronger current and *future* demand on x; consequently, if no additional strategy space is considered, he will restrain from adopting more aggressive fishing responses.

What are the implications if we compare the Stackelberg fishery with the particular case of a Cournot-Nash fishery leading to an FMNE? We can easily show the general conclusion that a Stackelberg leader will tend to partially compensate for the fishing patterns generated by changes in fully myopic Nash followers' productivity.

If followers increase their productivity, x^* will fall in the FMNE and in the Stackelberg fishery; however, in the latter case the fall will be smaller because the leader will adjust his optimal fishing effort downwards and hence alleviate the increasing demand on x. If followers' productivity falls, x^* will be lower in the Stackelberg case than it would have been if everyone were to behave as a fully myopic Cournot-Nash firm: the leader will take advantage of the followers' lower productivity by increasing his own fishing effort. However, the stronger preemptive incentive in favour of the leader will not fully neutralize the general trend towards a higher x^* that is generated by less productive followers. These arguments allow us to propose:

Proposition 4:

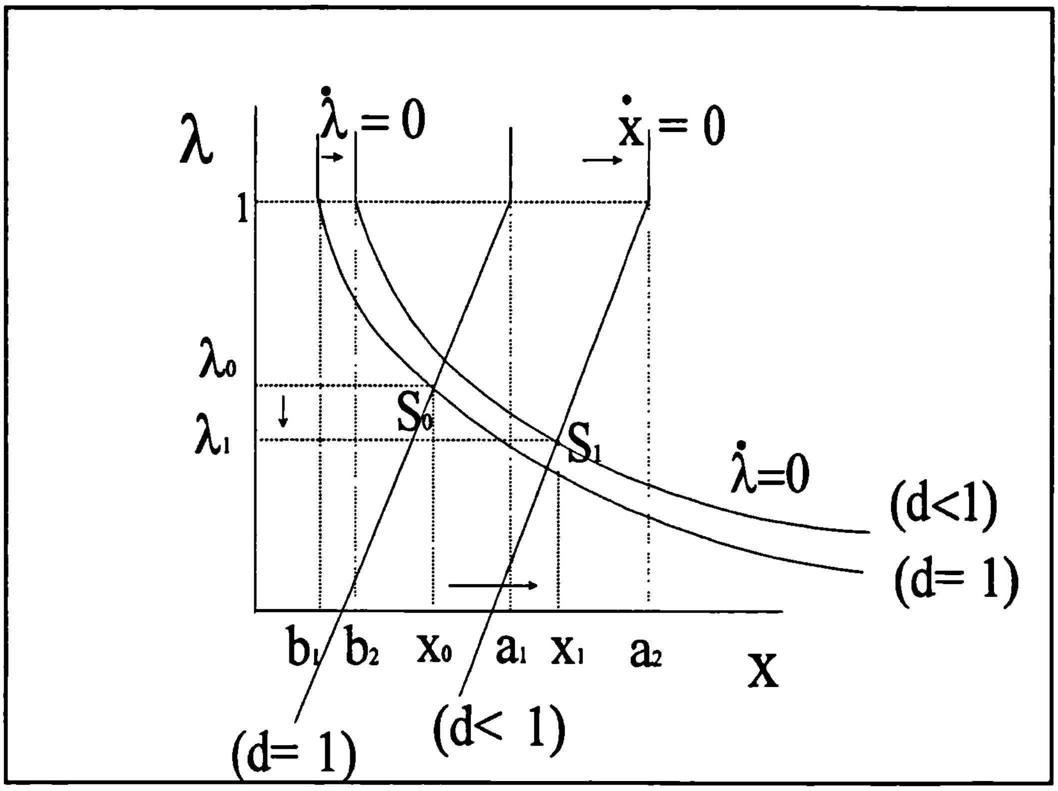
A dynamic profit optimizing Stackelberg leader will behave as a counteracting factor in fishing effort patterns induced by productivity changes among fully myopic Nash followers: higher (lower) harvesting ability displayed by followers will prompt the leader to a lower (higher) fishing effort strategy. However, in the long run it will dominate the direction of the changes brought about by the followers' new productivity.

Does the inefficient overfishing in the Stackelberg industry increase or decrease as the followers' productivity falls?

We know that both λ_w^* and λ_ℓ^* *always* fall as d decreases. We can also ascertain in (H.10) and (H.17) that $\lambda_w^*=\lambda_\ell^*$ if $d=0$, which is another way of referring to a single owner case. Given the price structure of our model, sole ownership coincides with Pareto efficiency and hence the equality that we obtain between the (social) shadow price of x and the (sole owner) leader's valuation of x.

Figure 6.11

Stackelberg steady state equilibria (d falling)



where:

$$a_1 = 1 - \frac{n}{2aw}$$

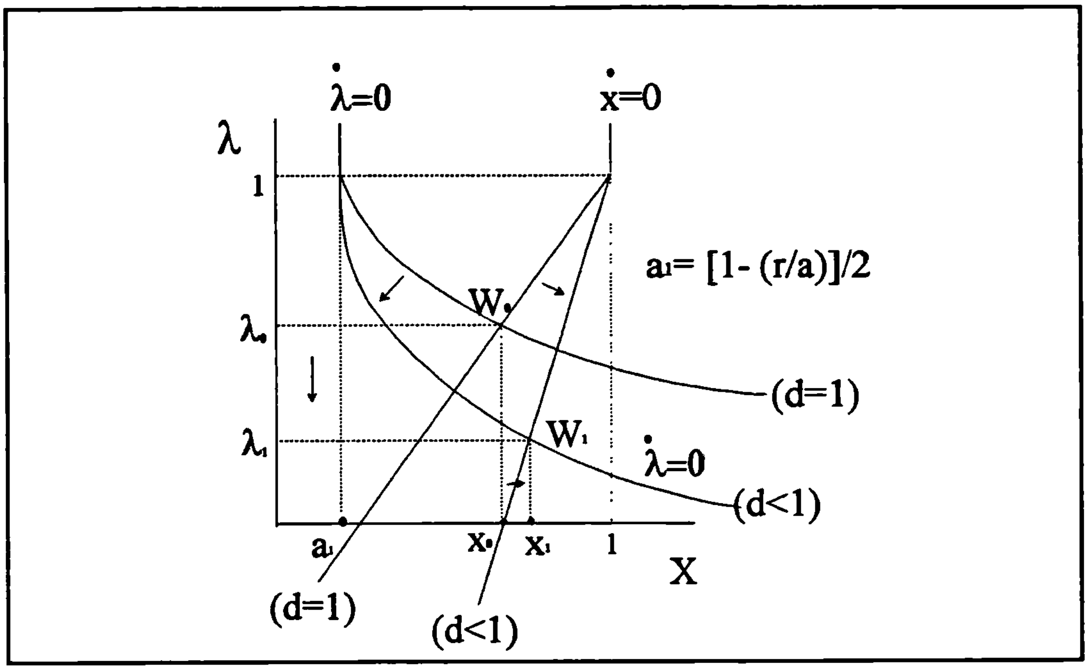
$$a_2 = 1 - \frac{nd^2}{2aw}$$

$$b_1 = \frac{1}{2}\left[1 - \frac{r}{a} - \frac{n}{2aw}\right]$$

$$b_2 = \frac{1}{2}\left[1 - \frac{r}{a} - \frac{nd^2}{2aw}\right]$$

Figure 6.12

First best welfare case: steady state equilibria



Therefore, as d falls from 1 to 0 it *must* be true that λ_w^* falls faster than λ_ℓ^*. This implies that as followers' productivity falls, the gap between both values is monotonically reduced. Given the validity of Lemma 1, the same must be true for the gap between x_w^* and x_s^*. This enables us to propose:

Proposition 5:

As followers' productivity falls, an initial situation of Stackelberg overfishing (that is, proposition 2 holds) will be monotonically reduced, disappearing in the limit as d approaches zero.

As d→0, the follower firms become unimportant relative to the leading firm. Therefore, the maximization of the leader's discounted profits leads to the maximization of the welfare function.

(6.I) Final remarks.

This chapter has focused on analysing overfishing in a dynamic setting by comparing welfare (first best and second best cases), Cournot-Nash and Stackelberg *steady state* solutions, for a differential *multi-firm* harvesting game under deterministic and non-cooperative oligopoly settings.

Our main contributions in this chapter to the economic analysis of multi-firm and common pool fisheries are:

(1) We develop an endogenous explanation of the incentives to overexploit a common pool resource, in cases when harvesters are dynamic profit optimizing agents. We formally model overfishing as the result of value gaps between the marginal social scarcity of fish stocks and the marginal value assigned to it by non-cooperative harvesting firms. This methodology allows us to distinguish between the concepts of static profit optimizing rules and inefficient harvesting myopia. Our first best welfare solution follows the standard definition in fishery economics. Our second best welfare solution illustrates the case of a welfare planner with limited control on the fishing efforts of the industry's harvesting fleet.

Our formal solutions for the scarcity values assigned to the fish stock have some similarities with value solutions obtained in Plourde and Yeung (1989), although they compare a dynamic multi-firm Cournot-Nash fishery only with a first best welfare case. We additionally consider a Stackelberg fishery and a second best welfare solution. We do not know other previous dynamic oligopoly fishery models with formal solutions for the marginal scarcity values assigned to the common pool fish stock. Clark (1980), Levhari and Mirman (1980), and Dockner et al. (1989), all of them considering dynamic *duopolistic* harvesting fisheries, do not formally analyse the marginal valuation of the remaining fish stock at the end of each time period.

(2) We also examine the consequences on overfishing from increasing the number of firms with access to the common pool natural resource. The formal analysis of this issue, within a *dynamic* oligopolistic harvesting setting, is a contribution to the literature on common pool fisheries.

To our knowledge, only Dockner et al. (1989) have a brief analysis of this type for the case of a *dynamic* Cournot-Nash fishery (section 6.F.2). This model, although with different assumptions to our discussion[39], derives similar steady state results to ours: as the number N of firms increases, the representative firm's stationary fishing effort falls; and when $N \rightarrow \infty$, harvesting becomes unprofitable: the representative firm shuts down. In Dockner et al.'s model this result stems from a decreasing demand price (as N increases) which in the limit case ($N \rightarrow \infty$) falls below the minimum average variable cost.

In our discussion, without pecuniary externalities and with closed-loop effort solutions, we also obtain decreasing individual fishing efforts as N increases, and a full closure stationary solution for $N \rightarrow \infty$. This result stems from an *increasingly lower* marginal productivity of the representative firm's fishing effort and also from declining biological growth returns (section 6.F.2). A larger number of firms increases *aggregate* harvesting in the contemporaneous period. The resulting lower end of period fish stock triggers a declining marginal productivity of fishing efforts. The assumption of a declining marginal productivity of fish stock helps each firm to increasingly *internalize* (by reducing her fishing effort) the higher scarcity of the common pool stock as the number N of firms increases. The internalization effect would clearly be smaller with harvesting functions which are linear in the fish stock (i.e., the commonly used *Schaefer* production function in fishery models).

[39] These authors center firms' strategic interactions on *pecuniary* (demand price) externality effects and obtain *open-loop* fishing effort solutions (see section 6.C.2).

(2.a) We show an (at first sight) counter intuitive result in a Cournot-Nash fishery where *all* firms behave as dynamic profit optimizing agents: *an increasing number of rivals implies increasing overfishing only for a limited (initial) range of number of firms*. This appears counter intuitive when it is compared with the limit result (for $N \to \infty$) traditionally derived within *static* discussions of overfishing: the open access solution of full rent dissipation (see Gordon, 1955; Dasgupta and Heal, 1979, ch.3; Cornes, Mason and Sandler, 1986, just to quote a few examples). In all these cases the full rent dissipation solution results from an (implicit) *increasing underestimation* of the higher scarcity value of the common pool resource as the number of firms increases. A key feature in this result is the assumption of individual harvesting functions which are proportional to the aggregate harvest, according to each firm's effort share in the industry's total fishing effort. As N increases, the individual share, of *identical* firms, in the aggregate fishing effort monotonically falls and hence each firm becomes less affected by the *congestion* problem modelled within the *aggregate* harvest function (e.g., see Table 6.1). This result reduces the individual incentives to internalize the increasing scarcity (higher congestion) of the fish population as N gets larger.

In our model, by contrast, *dynamic* profit optimizing firms have *increasing* incentives to internalize the higher scarcity value of the fish stock as N increases because lower fish stock levels imply: (i) increasing penalties on *each firm*'s marginal productivity of fishing effort, and (ii) *declining* biological returns for relatively overdepleted stock levels (in our model, $x_0 < 1/2$). The effect in (i) stems from the declining marginal harvesting productivity of fish stock, while the effect in (ii) is a consequence of the strictly concave growth function G(x) that we consider in our *dynamic* setting.

The effect in (i) needs not be present in real world industrial marine fisheries. The case of often collapsed *pelagic* fishing grounds is an example: in these cases the marginal harvesting productivity of fishing efforts can even increase when the fish population achieves relatively low levels (see chapter 2). On the other hand, the effect in (ii) can be absent if the biology of fish populations shows *depensatory growth* effects[40] at relatively low stock levels (chapter 2).

Our previous remarks highlight the importance, when it is the case of assessing the sources and magnitude of overfishing problems, of the type of dependence of harvesting returns on fish stock levels and the changes in marginal biological growth returns as fish populations become increasingly depleted.

(2.b) Section (6.G) examined the consequences of increasing the number of rival firms on the harvesting incentives of a single dynamic profit optimizing firm which competes with $n \geq 1$ *fully myopic* Cournot-Nash harvesters. We compared the harvesting equilibria that result from modelling the single dynamic optimizing agent as a: (i) Stackelberg leader (call it case *S*), (ii) another Cournot-Nash firm (case *N**), or (iii) a second best welfare planner (case *W2*). We compared these cases with a benchmark in which *all* harvesters are static profit optimizing Cournot-Nash agents (case *M*). We aimed to explore the overfishing consequences of introducing into a multi-firm static optimizing fishery a dominant firm which is a dynamic profit optimizing agent and may also have Stackelberg leadership attributes. This exercise was motivated by the empirical evidence described in chapters 3 and 4, suggesting the presence of industrial concentration in important marine industrial fisheries.

We obtained the following ranking of *stationary* fish stock solutions: $x_{W1} > x_N \geq x_{W2} > x_{N*} = x_S \geq x_M$. This ranking includes the first best welfare solution (case *W1*) of section (6.E), and the Cournot-Nash fishery (case *N*) of section (6.F), with *all N firms* being dynamic profit optimizing agents. The ranking above implies:

[40] In this case, lower population levels can imply increases in the marginal biological returns for relatively low x levels. This feature would retard the downward adjustment phase in fishing efforts and would contribute to magnify the overfishing problem.

(b.1) Our Stackelberg fishery implies lower overfishing than the case of a *fully myopic* Cournot-Nash fishery (case M) as long as the leading firm remains active in the fishery. For a sufficiently large (finite) number of rival firms, however, the dynamic optimizing leader decides to leave the fishery. Then the fishery becomes identical to a fully myopic Cournot-Nash fishery.

(b.2) The Stackelberg equilibrium is identical to the Cournot-Nash fishery with only one dynamic optimizing firm (case N^*). This occurs because the Stackelberg leader cannot *directly* affect the static optimizing followers' fishing efforts. In our model, without technological congestion and with price taking firms, the static optimizing followers use fishing effort decision rules which are independent of rivals' actions. Hence, in our Stackelberg model the leadership attribute merely implies that the leader recognizes the fish stock constraint.

(b.3) The second best welfare case, where the planner controls only the fishing effort of one harvester among other $n \geq 1$ firms, implies a higher stationary fish stock than the Stackelberg equilibrium. The planner internalizes, relative to the Stackelberg leader, more of the increasing scarcity of the fish population as the number of firms increases. The planner also decides, as the Stackelberg leader does, to leave the fishery for a sufficiently large (finite) number of non-cooperative rival harverters. Insofar as the planner is active, he manages to achieves a stationary stock solution identical to the case of the dynamic Cournot-Nash fishery of section (6.F).

(b.4) All previous cases imply overfishing when compared with the case of a first best welfare planner with full control over the fishing efforts of the industry's harvesting fleet.

Our analysis in section (6.G) is a complement to a few previous studies which have formally compared the stationary equilibria for *duopoly* harvesting games under Cournot-Nash and Stackelberg settings. To our knowledge, two papers have previously considered analyses of this type, by examining the case when *both* duopolists are dynamic profit optimizing agents. For instance, Levhari and Mirman

(1980) derived, in a fishery with *identical cost* firms, stationary solutions such that $x_{W1} > x_N > x_S$ and $H_{W1} > H_N > H_S$, with H denoting the industry's stationary aggregate harvest, W1 the first best welfare case, N the Cournot-Nash fishery, and S the leader/follower case. In this model the duopolists' strategic interaction is centered on the contribution of the common pool fish stock to each player's logarithmic utility function. In this setting, with both agents being dynamic optimizers, the Stackelberg fishery harvests more aggressively the common pool fish stock than the corresponding Cournot-Nash duopoly.

In Dockner et al.'s (1989) duopoly fishery firms' strategic interaction is centered on a *static* pecuniary (demand price) effect. When the Stackelberg leader has cost advantages over the followers, the resulting *static* solutions for the industry's aggregate fishing efforts are: $Z_S > Z_N$, with N and S denoting the Cournot-Nash and Stackelberg cases. Hence, in the *static solution* framework of Dockner et al. (1989) the Stackelberg fishery also harvests more aggressively the common pool fish stock (vs. the Cournot-Nash case) if the leader has cost advantages. The opposite effort ranking results when the Stackelberg leader has cost disadvantages versus the follower. In the latter case, the leader reduces his own fishing effort in order to allow for a higher demand price.

(3) In section (6.H) we examined the case of a single dynamic optimizing Stackelberg leader with *productivity advantages* over $n \geq 1$ fully myopic Nash followers. An interesting result is that the dynamic optimizing Stackelberg leader behaves as a *counteracting* factor in fishing effort patterns induced by productivity changes among the fully myopic Nash followers. For instance, if followers' relative productivity increases the Stackelberg leader will reduce his fishing effort, and vice versa. An implication of this is that the dynamic optimizing leader will not engage in harvesting wars if his rivals become more productive.

(6.J) APPENDICES.

(6.1) Convergence to steady state equilibrium: welfare case.

The dynamic system is given by $G(x,\lambda)$ and $S(x,\lambda)$ in (E.10)-(E.11). Linearizing this system around the steady state equilibrium (x^*,λ^*) implies:

$$\begin{bmatrix} \dot{x} \\ \dot{\lambda} \end{bmatrix} = \begin{bmatrix} G_x & G_\lambda \\ S_x & S_\lambda \end{bmatrix}_{ss} \begin{bmatrix} x-x^* \\ \lambda-\lambda^* \end{bmatrix} \tag{1.1}$$

where:

$G_x = [a(1-x^*) - A(1-\lambda^*)] - ax^* = -ax^* < 0$, because $[.]=0$ at steady state. (A is given in (E.10))

$G_\lambda = Ax^* > 0$

$S_x = 2a\lambda^* > 0$

$S_\lambda = r-a + 2ax^* + A(1-\lambda^*) > 0$ because $\lambda^* < 1$ and $x^* > (1/2)[1-(r/a)]$

Given this, the Jacobian matrix J has a negative determinant, $|J| = G_xS_\lambda - S_xG_\lambda < 0$. We know that $|J|_{ss} = r_1r_2$, where r_i are eigenvalues of J, such that the temporal solutions (trajectories) $\theta(t) = (x(t)-x^*,\lambda(t)-\lambda^*)'$ correspond to:

$$\theta(t) = c_1v_1\exp\{r_1t\} + c_2v_2\exp\{r_2t\} \tag{1.2}$$

with c_i constants and v_i the corresponding eigenvectors.

Since $|J|_{ss} < 0$, we know that r_1,r_2 are both real and have opposite signs (say $r_1 > 0$, $r_2 < 0$). Recall that r_i are real and different if $\Delta > 0$, where $\Delta = (tr(J))^2 - 4|J|$ and $tr(J) = r_1 + r_2$.

Therefore, given $|J| < 0$ we know that the steady state equilibrium is a saddle point with one convergent (phase) trajectory or stable arm (more details in Beavis and Dobbs, 1990, ch.5.5).

We also know that $tr(J) = G_x + S_\lambda \Rightarrow tr(J) = r > 0$. This implies that $r_1 > |r_2|$. Therefore, unless initial conditions rule out the possibility that $c_1 > 0$ (see equation 1.2), system (E.10)-(E.11) will not converge to the steady state equilibrium

(x^*,λ^*) as $t \to \infty$. In other words, convergence to the steady state calls for $c_1=0$. This imposes a necessary constraint on the initial conditions of the system. The fulfillment of this constraint on initial conditions is tantamount to the imposition of a transversality condition (Chiang, 1992, p.124)

(6.2) Convergence to steady state equilibrium: Cournot-Nash case.

The dynamic system is given by (F.8)-(F.9). Linearizing this system around steady state equilibrium x^*,λ^* (both >0), implies:

$$\begin{bmatrix} \dot{x} \\ \dot{\lambda} \end{bmatrix} = \begin{bmatrix} G_x & G_\lambda \\ S_x & S_\lambda \end{bmatrix} \begin{bmatrix} x-x^* \\ \lambda-\lambda^* \end{bmatrix}, \quad J= \begin{bmatrix} G_x & G_\lambda \\ S_x & S_\lambda \end{bmatrix}_{ss}$$

where:

$G_x = [a(1-x^*) - A(1-\lambda^*)] - ax^* = -ax^*<0 \quad (A= N/(2w))$

$G_\lambda = Ax^*>0$

$S_x = 2a\lambda^*>0$

$S_\lambda = r\text{-}a + 2ax^* + [1/(4w)][1- N\lambda^* + N(1-\lambda^*)]$

$\quad = [1/(4w)][(1/\lambda^*) - N\lambda^*] \Rightarrow$

$S_\lambda >(<) 0$ if $\lambda^*<(>) 1/\surd N$

Therefore:

(1) if $\lambda^*< 1/\surd N$, $S_\lambda>0 \to |J| = G_xS_\lambda - G_\lambda S_x <0$

Consequently, (x^*,λ^*) is a saddle point.

(2) if $\lambda^*> 1/\surd N$, $S_\lambda<0$, then sign($|J|$) is given by:

$|J| = -[(ax^*)/(4w)][(1/\lambda^*) + 3N\lambda^*] <0 \quad \forall\, x^*,\lambda^* >0$

Accordingly, steady state (x^*,λ^*) is invariably a saddle point.

Convergence to the steady state equilibrium is guaranteed if the absolute value of the negative eigenvalue (call it r_1) is greater than that of the positive root (r_2). Bear in mind that $tr(J)= G_x + S_\lambda = r_1 + r_2$.

In case (2), tr(J) < 0; therefore, independently from initial conditions, our system will hit the stable arm of the saddle point and it will converge to steady state as $t \to \infty$.

In case (1), sign[tr(J)] is ambiguous. In fact, tr(J) = [r - n/(4w)]. Hence, tr(J) > (<)0 if r > (<)n/(4w). If tr(J) < 0, convergence to the steady state is guaranteed, independently from initial conditions. If tr(J) > 0, we need to impose a constraint on the initial conditions of the system such that the corresponding transversality condition is fulfilled (equation (F.7)).

(6.3) Proof for Proposition 1.

We concentrate on a positive steady state solution (x^*, λ^*). Nash-Cournot and welfare solutions satisfy locus $\dot{x}=0$. This locus implies that if $(\lambda^*)^w > (\lambda^*)^n$, then $(x^*)^w > (x^*)^n$.

Steady state solutions (F.10) and (F.11) imply:

$$sign\ (\lambda^w - \lambda^n) = sign \left\{ -F + \left[F^2 + Q + 2F \left(1 + \frac{1+4Rw}{3N} \right) \right]^{1/2} - Q^{1/2} \right\} \tag{3.1}$$

where:

$$F = \frac{1}{3}\left(1 - \frac{1}{N}\right) > 0$$

$$Q = J^2 + \frac{4}{3N} > 0$$

$$J = 1 - \frac{1+4Rw}{3N}$$

Since F and Q are positive, it must be true that $(\lambda^*)^w > (\lambda^*)^n$ if (4Rw)/(3N) > 0. As long as this condition holds, then it is also true that $(x^*)^w > (x^*)^n$.

(6.4) Proof for $\partial\lambda_w/\partial N>0$

Rewrite equation (F.10) as follows :

$$\lambda_w^* = \frac{1}{2}\left(P + (P^2 + 4/3)^{1/2}\right) \tag{4.1}$$

With P$\equiv$ [2/3-(4Rw)/3N]. Note that $\partial P/\partial N = (4Rw)/(3N^2)>0$, given that R=(r+a)>0 and w>0. From (4.1) we obtain that :

$$\frac{\partial\lambda_w^*}{\partial N} = \frac{1}{2}\frac{\partial P}{\partial N}\left[1 + P\,(P^2 + 4/3)^{-1/2}\right] \tag{4.2}$$

We do not know the sign of P *a priori*. If P$\geq$0 then $\partial\lambda_w^*/\partial N>0$ given that $\partial P/\partial N>0$. If P<0, we can write (using equation (4.2)) :

$$\begin{aligned} Sign\left[\frac{\partial\lambda_w}{\partial N}\right] &= sign\left[1 - \left((|P|^2)^{1/2}\right)(P^2 + 4/3)^{-1/2}\right] \\ &= sign\left[1 - (1+ 4/(3P^2))^{-1/2}\right] \end{aligned} \tag{4.3}$$

Because invariably $P^2>0$, from (4.3) we can deduce that if P<0 then $(\partial\lambda_w/\partial N)>0$. Therefore, independently of P$\geq$0 or P<0, invariably $(\partial\lambda_w/\partial N)>0$, $\forall N\geq 1$.

(6.5) Proof for $(\partial\lambda_s/\partial N)>0$.

Rewrite equation (F.11) as follows :

$$\lambda_s^* = \frac{1}{2}\left[J + (J^2 + 4/(3N))^{1/2}\right] \tag{5.1}$$

with J$\equiv$ [1-(1+4Rw)/3N]. Taking the partial derivative of (5.1) with respect to N, we obtain that sign $[\partial\lambda_s/\partial N]$ is equivalent to:

$$sign\left[\frac{\partial J}{\partial N}\left(1+J(J^2+4/(3N))^{-1/2}\right)-\left[\frac{2}{3N^2}\right](J^2+4/(3N))^{-1/2}\right] \tag{5.2}$$

Our proof requires that the expression in (5.2) be positive. Multiplying the expression in (5.2) by $(J^2+4/(3N))^{1/2}>0$ and then dividing the result by $\partial J/\partial N=[(1+4Rw)/(3N^2)]>0$, we obtain that (5.2) is positive if:

$$(J^2+4/(3N))^{1/2}>\frac{2}{3N(1-J)}-J \tag{5.3}$$

where $(1+4Rw) = 3N(1-J)$. Now multiply (5.3) by $(J^2+4/(3N))^{1/2}$; hence (5.3) becomes:

$$J^2+4/(3N)>C(J^2+4/(3N))^{1/2} \tag{5.4}$$

with $C \equiv [2/(3N(1-J)) - J]$.

We do not know the sign of C *a priori*. If $C\leq 0$ then (5.4) is invariably true. Now, if $C>0$, then (5.3) must be fulfilled in order to obtain $(\partial\lambda_n/\partial N)>0$. Squaring both sides of the inequality in (5.3), cancelling the symmetric term J^2 on both sides and then dividing the result by $(4/(3N))$, we obtain:

$$3N(1-P)^2 > 1 - 3NP + 3NP^2 \tag{5.5}$$

Solving for the square term on the left hand side of (5.5), we obtain that the fulfillment of (5.3) implies :

$$3N(1-P) > 1 \tag{5.6}$$

But 3N(1-P)=1+4Rw. Hence (5.6) is equivalent to the condition 4Rw=4(r+a)w>0. Therefore, as long as 4Rw>0 we invariably obtain that $(\partial\lambda_n/\partial N)>0$.

Appendix (6.6):

(I) Consider the limit behaviour of λ_w (given by F.10) when $N\to\infty$. This implies:

$$\lim_{N\to\infty} \lambda_W = \lim_{N\to\infty} \frac{1}{2}\Big((2/3) - (T/N) + \left[(2/3 - T/N)^2 + 4/3\right]^{1/2}\Big)$$

with T=4Rw/3>0.

Given that $\lim_{N\to\infty} T/N = 0$, we can easily verify that $\lim_{N\to\infty} \lambda_w = 1$.

(II) Consider now the limit behaviour of λ_n when $N\to\infty$.

By direct inspection of (F.11) we can verify that $\lim_{N\to\infty} \lambda_n = 1$.

Appendix (6.7): Proposition 2.

To obtain $\lambda_w^* > \lambda_S^*$, it must be true that:

$$D\left[\frac{1}{N}-1\right] + \sqrt{\left[\frac{D}{N}\right]^2 + \frac{4}{3N^2}} > \sqrt{D^2 + \frac{4}{3N^2}} \qquad (7.1)$$

with D<0 as a necessary condition, D given in (G.14).

Given D<0, taking $(.)^2$ on (7.1) does not change the sign of inequality. Simplifying from this we arrive at that (7.1) requires:

$$D\left[\frac{D}{N} + \sqrt{\left[\frac{D}{N}\right]^2 + \frac{4}{3N^2}}\right] < 0 \qquad (7.2)$$

Since $D<0$, this condition requires the expression between large brackets to be positive. Direct inspection shows that the value of the expression under the square root is *invariably* greater than $|D/N|$. Then the expression between the large brackets is always positive. Therefore, $D<0$ is also a *sufficient* condition to obtain $\lambda_w^* > \lambda_S^*$.

Appendix (6.8) :

Define $T \equiv \frac{4Rw}{3} > 0$. *Hence sign* $\left[\frac{\partial \lambda_w}{\partial d}\right]$ is equal to:

$$sign\left[-T\frac{\partial M^{-1}}{\partial d} + \frac{\partial}{\partial d}\left\{\left[TM^{-1} - \frac{2}{3}\right]^2 + \frac{4}{3}\right\}^{1/2}\right] \tag{8.1}$$

with $M=(1 + nd^2)$. Hence $\partial M^{-1}/\partial d = -(1 + nd^2)^{-2}(2nd) < 0$.
Therefore $-T(\partial M^{-1}/\partial d) > 0$. We can write equation (8.1) as :

$$-T\frac{\partial M^{-1}}{\partial d}\, sign\left[1 - \frac{(TM^{-1} - 2/3)}{[(TM^{-1} - 2/3)^2 + 4/3]^{1/2}}\right] \tag{8.2}$$

Denote $U = (TM^{-1} - 2/3)$. If $U<0$, then necessarily $\partial\lambda_w/\partial d > 0$. If $U>0$,

$$sign\left[\frac{\partial \lambda_w}{\partial d}\right] = sign\left[1 - \frac{1}{[1 + 4/(3U^2)]^{1/2}}\right] \tag{8.3}$$

Given that invariably $U^2>0$, the sign of expression in (8.3) is invariably positive. Therefore, invariably $\partial\lambda_w/\partial d > 0$.

Appendix (6.9) :

We need to prove that $\partial x^*/\partial d<0$, with x^* given by (H.8). Deriving the latter with respect to d, we obtain that $\partial x^*/\partial d<0$ requires: $C1 \equiv [(\partial M/\partial d)(1-\lambda_w) - M(\partial\lambda_w/\partial d)]>0$, with $\partial M/\partial d>0$, $M=(1+nd^2)>0$, $(1-\lambda_w)>0$ and $\partial\lambda_w/\partial d>0$. Using (H.10), we know that:

$$\frac{\partial\lambda_w}{\partial d} = \frac{1}{2}\,TM^{-2}\,\frac{\partial M}{\partial d}\left[1 + P(P^2 + 4/3)^{-1/2}\right] \tag{9.1}$$

with $T\equiv(4/3)Rw>0$ and $P\equiv(2/3 - TM^{-1})$ (>)(<) 0.

Hence $C1>0$ requires:

$$(1-\lambda_w) - \frac{TM^{-1}}{2}\left(1 + P(P^2 + 4/3)^{-1/2}\right)>0 \tag{9.2}$$

Using (H.10), $(1-\lambda_w) = (1 - P/2) - (1/2)(P^2 + 4/3)^{1/2}$. Rearranging terms in equation (9.2), we obtain that $C1>0$ requires (replacing $TM^{-1} = (2/3 - P)$ in (9.2)):

$$(4/3)(P^2 + 4/3)^{1/2} > (2/3)P + 4/3 \tag{9.3}$$

Multiplying equation (9.3) by (3/2) and then squaring both sides of the inequality, we obtain:

$$3P^2 - 4P + 4/3 > 0 \tag{9.4}$$

We do not know the sign of P *a priori*. If $P\leq 0$, (9.4) is invariably true, hence $C1>0$ and therefore $\partial x^*/\partial d<0$. Solving for the equation $(3P^2-4P+4/3)=0$, we obtain the unique solution $P=2/3$. Therefore, if $P<2/3$ the inequality in (9.4) is fulfilled. Now, if $P>0$ then necessarily $P<2/3$ given that $TM^{-1}>0$ (see definitions in (9.1)). Therefore, independently of whether $P\leq 0$ or $P>0$, we invariably obtain that $C1>0$ and hence $\partial x^*/\partial d<0$, with x^* given by (H.8).

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